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ALASKAN STREAM CIRCULATION AND EXCHANGES THROUGH THE ALEUTIAN ISLAND PASSES: 1979-2003 MODEL RESULTS

by

Ricardo Roman

March 2006

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13. ABSTRACT

The objective of this research is to examine the long-term variability in the flow of the Alaskan Stream, as well as the northward transport through three selected Aleutian Island passes. Taking into consideration that upper ocean water properties and in part circulation in the Bering Sea are derived from northward flow through the Aleutians, it is important to understand how different anomalies in the movement of the Alaskan Stream might alter this communication with the Bering Sea. In the past, observational data has frequently underestimated the strength of the Alaskan Stream, basing measurements of geostrophic velocity on levels of no motion at either 1000 m or 1500m. Using a 25-year (1979-2003) ice-ocean model the results presented in this study indicate that the Alaskan Stream transport is not only significantly larger than previously reported, but that westward flow extends to depths >4000 m. Research has also been conducted on the magnitude and frequency of eddy-induced changes to the path and strength of the Alaskan Stream. These changes can significantly impact northward flow through the Aleutian passes. This region is also of particular interest to the U.S. military. As recent observational and model studies have predicted future reductions of sea-ice in the Arctic, foreign military traffic might increase through the North Pacific Ocean, specifically the Aleutian Island passes, as countries begin to explore and conduct exercises within the Arctic region. This would increase the importance of understanding of acoustic properties within the Aleutian Island region, which is of relevance to Undersea Warfare.

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ALASKAN STREAM CIRCULATION AND EXCHANGES THROUGH THE ALEUTIAN ISLAND PASSES: 1979-2003 MODEL RESULTS

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requirements for the degree of

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ABSTRACT

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This work is dedicated to my beautiful wife Meghan, who has given me constant support throughout this process.

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I. INTRODUCTION

A. BACKGROUND OF ALASKAN STREAM AND ALEUTIAN PASSES RESEARCH

The Alaskan Stream is an intense narrow (~50-80 km) and deep (>3000 m) current, which represents the northern boundary of the Pacific sub-arctic gyre (Stabeno and Reed, 1992, Reed and Stabeno, 1999). Flowing from east to west, the Alaskan Stream begins in the upper Gulf of Alaska and continues westward near 180^0W (International Date Line). At this point, the Alaskan Stream begins to break from the bathymetry, partly continuing westward to join the southward flowing Kamchatka Current and complete the deep Sub-Arctic Gyre, while a large portion flows northward into the Bering Sea through the western Aleutian Island passes, mainly Near Strait (Thomson, 1972; Stabeno and Reed, 1992; Chen and Firing, 2006). To the north it is bordered by the Aleutian Island arc, which acts as the western and eastern boundary for the current as it moves past the International Date Line (180^0).

To the south, the Alaskan Stream is bounded by a deep eastward flowing current (Reed, 1969; Reed, 1970; Warren and Owens, 1988; Maslowski et al. 2005; Chen and Firing, 2006), which flows just above the Aleutian rise. This deep eastward flowing current, better known as the eastward jet (Reed, 1969; Reed, 1970; Warren and Owens, 1988), partially turns northward between 167^0W and 171^0W, supplying an increase in strength to the total volume transport of the Alaskan Stream (Maslowski et al. 2005). Warren and Owens (1988) have identified the eastward jet in the vicinity of

175^{0}W and 165^{0}W in June 1981 and again near 175^{0}E and 175^{0}W in August 1982, tracking it back through the Emperor Seamount chain and originating off the Zenkevich Rise near Japan. Volume transport of the eastward jet has been measured on several occasions, most notably by Warren and Owens (1988) who estimated an eastward transport of ~20 Sv, which ~5-10 Sv existed below 1500 m.

The Alaskan Stream is also linked to the Bering Sea, supplying warm and relatively freshwater, its northward flow through the Aleutian passes helps drive the Aleutian North Slope Current and Bering Slope Current. Of the Aleutian passes, Amukta Pass, Amchitka Pass, and Near Strait represent the main conduits through which Alaskan Stream water enters the Bering Sea (Clement, 2005), while the major outflow is the Kamchatka current.

The first recorded documentation of the Alaskan Stream was by Veniaminov in 1840 (Roden, 1995), stating that a swift current just south of the Aleutian Island arc moved towards the southwest. Favorite (1974) further investigated the magnitude of both the Alaskan Stream and flow through the Aleutian passes, estimating that the mean northward transport through the Aleutian Islands was ~14 Sv, while his estimates for the strength of the Alaskan Stream were only 5 to 10 Sv (Roden, 1995). These measurements, which were referenced to a depth of 1000 m, have since been re-evaluated to take the full depth of the Alaskan Stream into account. Warren and Owens (1988), as well as Reed and Stabeno (1999), have since examined the magnitude of the Alaskan Stream both at the surface and at great depths (~6900 m). Their research has led to new measurements regarding the strength and influence of the

Alaskan Stream and its flow through the Aleutian passes. Extending their investigation of the Alaskan Stream to depths greater than 4000 m, Warren and Owens (1988) calculated a westward transport of 28 Sv, and estimated a 5 Sv westward transport below 1500 m. Reed and Stabeno (1999) explored even further down in the water column (~6800 m) and found similar values for the volume transport, measuring a westward transport of 25 Sv at 173.5^{0} W, while the surface velocity equaled ~123 cm s^{-1}. These measurements, while becoming more consistent, reveal the need to further explore the true strength of the Alaskan Stream below depths of 1000-1500 m, which typically provided bottom limits of geostrophic flow estimates. Also, data collection in the past has relied heavily upon widely spaced point measurements gathered from either conductivity-temperature-depth (CTD) recorders or current moorings, which could provide an inaccurate representation of the volume transport (Roden, 1995). More recently, investigations near 180^{0}W have identified an even stronger westward flow, estimating an Alaskan Stream volume transport of 38.8 Sv, based on a 6000dBar reference level (Roden, 1995; Chen and Firing, 2006).

Variations of flow in the Alaskan Stream, as well as through the Aleutian passes, play a key role in the delicate balance of both the water properties and circulation within the Bering Sea. Major disturbances created by southward shifts in the Alaskan Stream and eddies propagating along the Aleutian Island arc produce the largest deviations, and are explored in several different studies. One of the more recent studies concerning flow anomalies in the Alaskan Stream is

presented by Stabeno and Reed (1992). They concluded, gathering volume transport data through the major Aleutian passes that northward flow into the western Bering Sea, from the Alaskan Stream, ceased from summer 1990 through fall 1991. Typically, western Alaskan Stream water flows through Near Strait into the Bering Sea, recording a northward volume transport of ~10 Sv (Favorite, 1974; Stabeno and Reed, 1992). During summer 1990 to fall 1991 though, several satellite-tracked drifting buoys displayed a lack of inflow into the Bering Sea from the North Pacific Ocean, instead continuing westward rather than along the Aleutian Island arc (Stabeno and Reed, 1992). The suspected cause of the lack of exchange between the two bodies of water was attributed to a southward shift in the Alaskan Stream resulting from an inertial effect, which resulted in an appreciable cooling of the subsurface water ($<3.8^{0}$C as opposed to $>4.1^{0}$C), and a decreased net northward flow of ~3 Sv in Near Strait (Stabeno et al. 1999). Crawford et al. (2000) investigated the life-span of eddies along the Aleutian Island arc using TOPEX/Poseidon data, observing that they increased in height as they moved further westward. While it is speculated that the effect of eddies propagating along the Alaskan Stream can have a major effect on the water properties and circulation of the Bering Sea (Okkonen, 1996), to our knowledge no long-term data exist to realize the extent of these anomalies.

The primary goal of this research is to use a numerical model to investigate the long-term volume, heat, freshwater, and salt fluxes over a 25-year period (1979-2003). Also, the variability of these four factors will be studied in order to gain an understanding of significant

deviations from the mean in the region. Another major objective of this study is to examine the influence of eddies propagating along the Alaskan Stream, and their effect on the exchange of water through the Aleutian Island passes. The depth of westward flow associated with the Alaskan Stream, will also be studied. Model data will be reinforced through validation with observational data, to include volume transport, water column velocities, eddy propagation, and inflow into the Bering Sea.

B. NAVY RELEVANCE

New research (Clement, 2005; Maslowski et al., 2006; McNamara 2006) and modeling studies have shown that a significant decline in the polar ice-cap has occurred in recent years. As the only body of water influencing the Arctic Ocean from the Pacific, the Bering Sea plays a significant role in determining the future of this region. More importantly, upper ocean properties and in part circulation in the Bering Sea is derived from northward flow through the Aleutian Island passes. As a result, it is essential to understand how variations in the Alaskan Stream might effect both the communication between the North Pacific Ocean and the Bering Sea, and the acoustic properties within the region. Also, a shift towards increased ice-free conditions is expected to encourage military ship traffic from the Pacific to conduct exercises within the Arctic Ocean. Consequently, regions such as the Aleutian Island passes, which represent the only accessible waterways into the Bering Sea from the North Pacific, might become a major thoroughfare for countries such as North

Korea, India, and China. For this reason, it is imperative to understand how anomalies in the Alaskan Stream, and exchanges through the Aleutian Island passes, might affect the water property within this region, which plays an important role in Undersea Warfare.

The implications of commercial shipping (e.g. oil tankers, cargo ships) can also pose as a serious concern not only to the Alaskan habitat, but also as a possible security threat to the United States. Cargo ships entering the North Pacific from the Arctic Ocean will have to travel through the Aleutian Island passes, increasing the area of surveillance for the U.S. armed forces in search of illegal shipments. Also, the possibility of an increase in oil tankers using the Arctic passage, as a means of moving shipments from the Pacific to the Atlantic, dramatically increases the chances of another Exxon Valdez scale disaster. Studying the flow of water within the Alaskan Stream, and the exchanges through the Aleutian Island passes, will help both the Navy and the Coast Guard better prepare in the event of another disaster.

II. MODEL DESCRIPTION

The coupled sea ice-ocean model domain (Figure 1) extends from the North Pacific, encompassing the Sea of Japan to the Gulf of Alaska, to the Bering Sea, Arctic Ocean, Canadian Archipelago, Barents and Nordic seas, and into the North Atlantic Ocean (Maslowski et al. 2005). For the purposes of this study, the region of interest within the ice-ocean model is shown in Figure 1 with a black rectangular box. Reaching as far east as Kodiak Island, and as far west as Bowers Ridge, the examined area includes the path of the Alaskan Stream, as well as northward flow through the Aleutian Island passes. The horizontal grid spacing in the model is $1/12^0$ (~9 km) and 45 vertical layers are used to represent depths extending to 6250 m. Due to the aforementioned high horizontal resolution, the model is also said to be eddy-permitting. An artificial channel extends across Canada to ensure the exchange of water between the Pacific and Atlantic Oceans, balancing the northward volume transport through the Bering Sea. The model bathymetry was derived from both the International Bathymetric Chart of the Arctic Ocean (2.5 km resolution north of 64^0N) and ETOPO5 (5 km resolution for the region south of 64^0N). The Pan-Arctic model was initialized with climatological, 3-dimensional temperature and salinity fields (Steele et al., 2000) and integrated for 48 years in a spin-up mode.

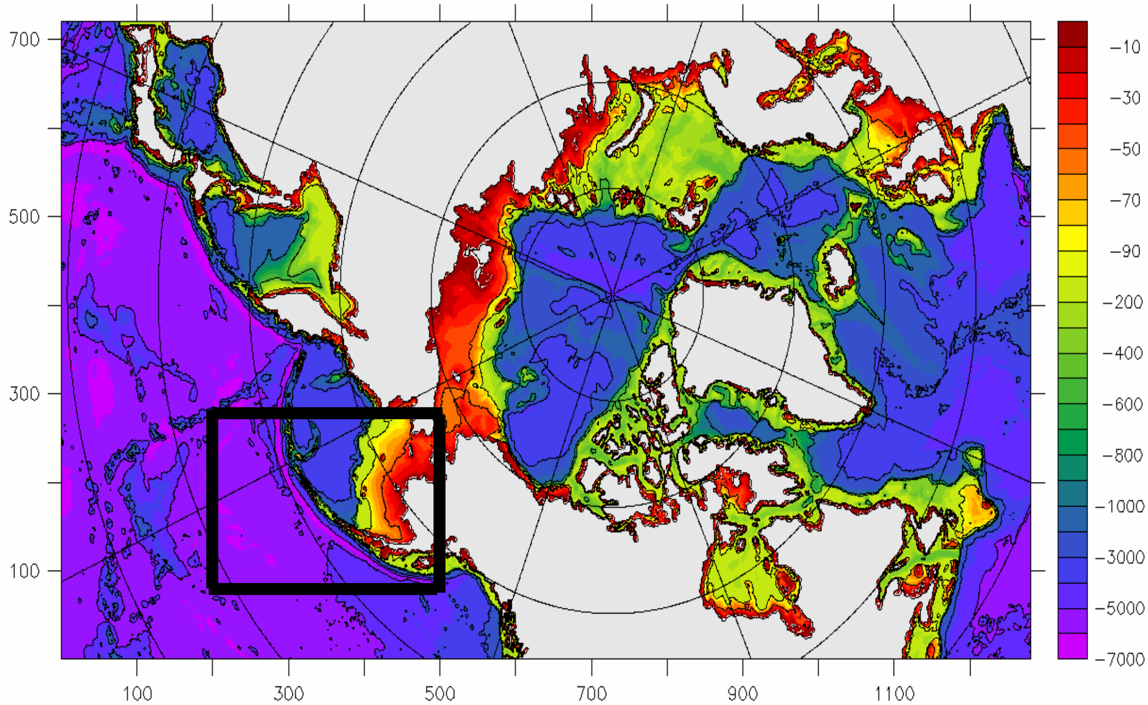


Figure 1. Pan-Arctic model domain and bathymetry. The black rectangular box represents the region of interest. The color scale designates the depth of the area.

III. RESULTS

A. THE ALASKAN STREAM

The Alaskan Stream is the northern boundary current of the Pacific (cyclonic) Sub-Arctic Gyre, and is bordered to the north by the Aleutian Island Arc. The fast moving stream has a twenty-five-year (1979-2003) mean modeled transport of ~45-56 Sv (Maslowski et al. 2005), gradually increasing as it moves west. Flowing along the Aleutian Islan arc, the Alaskan Stream has the potential to extend deep into the Aleutian trench, demonstrating westward flow below 4000 m. The Alaskan Stream, through passes along the Aleutian Islands, significantly affects the flow and properties of the water within the Bering Sea. The largest transports to the east of 180^{0}W occur through Amchitka, Amukta, and Unimak passes. To the south Alaskan Stream an eastward moving stream travels along the Aleutian rise. A portion of this flow eventually increases the Alaskan Stream’s volume transport via recirculation occurring near section AS7 (Figure 2). While the Alaskan Stream’s mean modeled transport is simulated along the Aleutian trench, eddies introduce significant changes in its pathway and/or transport by shifting the current to the south and consequently modulating exchanges through the Aleutian Island passes.

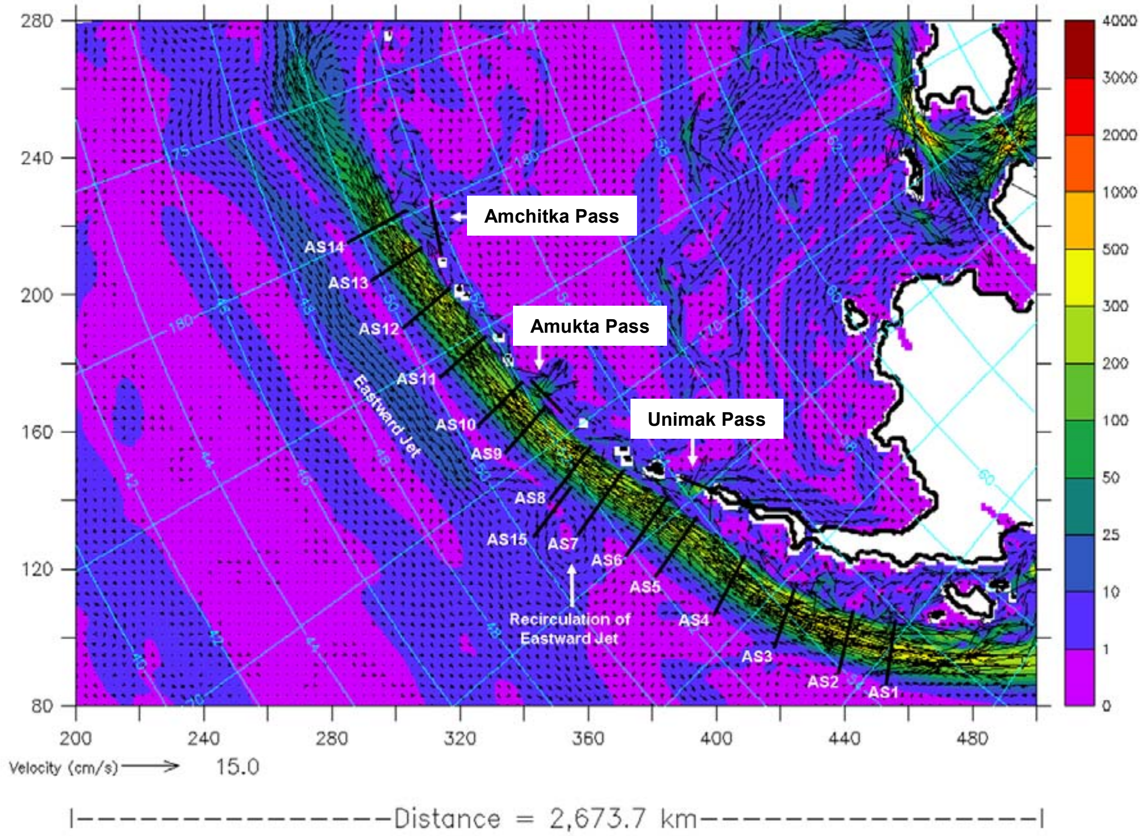


Figure 2. Twenty-five-year (1979-2003) mean circulation and total kinetic energy over the entire water column (0-6250 m). Color shading represents the total kinetic energy (cm^2 s^{-2}).

1. Alaskan Stream Circulation

The Alaskan Stream extends from the head of the Gulf of Alaska to the most western Aleutian Islands. In the mean state, the Alaskan Stream is a narrow, deep, fast moving current which intensifies as it flows westward along the southern edge of the Aleutian Island arc. Carrying relatively warm, fresh water it provides much of the upper ocean water properties of the Bering Sea. The modeled volume transports across fourteen Alaskan Stream cross sections (Figure 3) also show that there are significant

fluctuations of the westward flow. Although irregular in nature, these transport anomalies of the Alaskan Stream can significantly reduce, or even reverse the flow of the stream. The reversals are typically seen in the cross sections west of Amukta Pass, with the exception being the flow reversal in 2002 at section AS1, and can reach a maximum modeled transport of ~-30 Sv. The decrease, and sometimes reversal of the Alaskan Stream during these time periods also seem to increase in duration as it moves westward, typically remaining below the mean volume transport for as long as a year. Beginning at section AS7 the mean modeled volume transport of the Alaskan Stream shows a significant increase (Figure 4). This is thought to be a result of the recirculation from the eastward-flowing Sub-Arctic Current northward into the Alaskan Stream (Maslowski et al. 2005; Warren and Owens, 1988). The Sub-Arctic Current (Eastward Jet), becoming wider and weaker as it flows east of 170^{0}W, develops a branch moving northward toward the Alaskan Stream due to an increase in depth (~5000 m) in the Aleutian rise. As it moves northward, this portion of the eastward jet eventually merges with the westward moving Alaskan Stream, increasing the net volume transport.

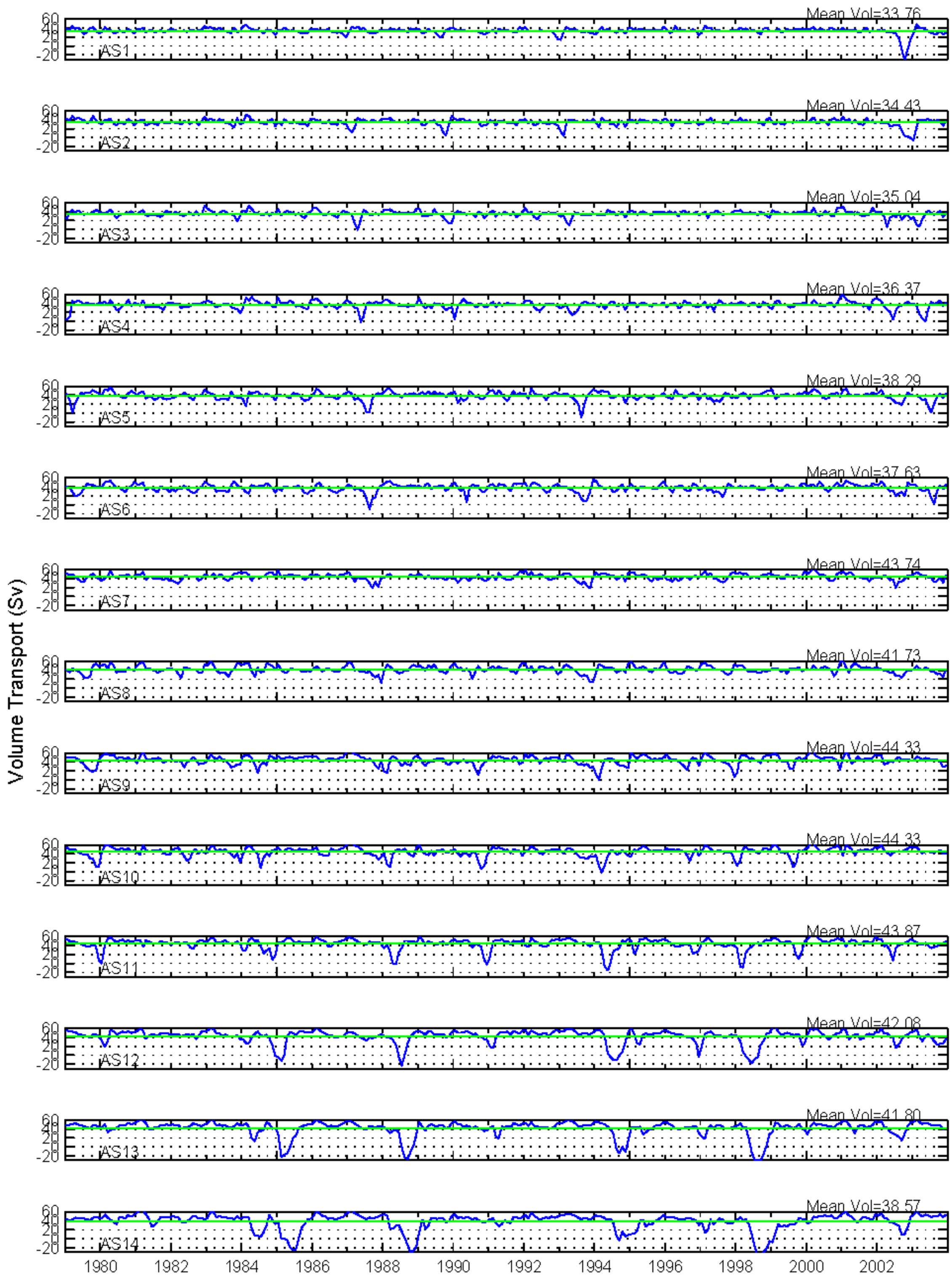


Figure 3. Monthly mean volume transport over a 25-year time series (1979-2003). The blue line shows time-varying transports. Positive values indicate westward transports. The 25-year mean is represented by the green line.

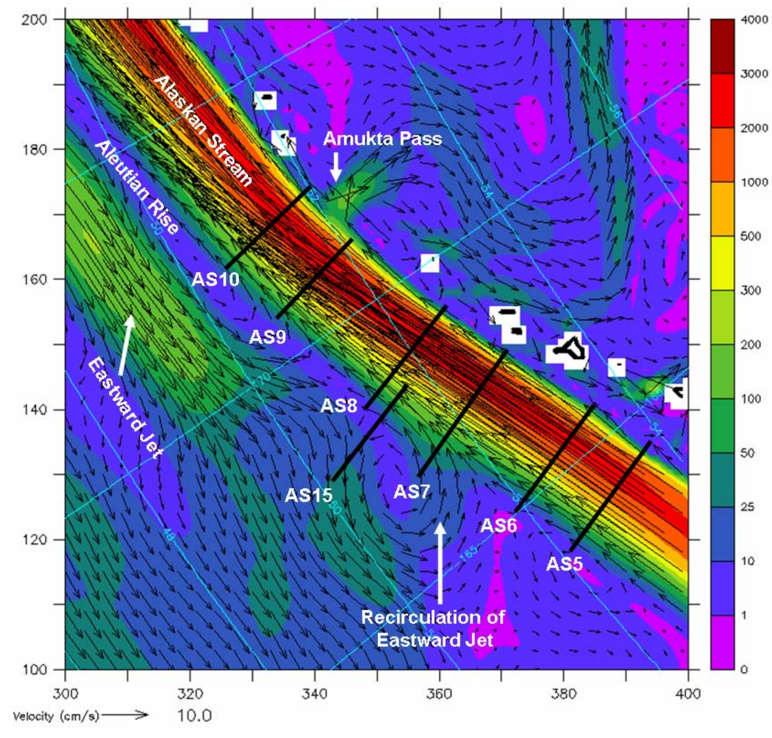


Figure 4. Twenty-five-year (1979-2003) mean circulation and total kinetic energy in the upper 65 m of the recirculation of the Sub-Arctic Gyre northward into the Alaskan Stream near section AS7. Color shading represents the total kinetic energy (cm^2 s^{-2}).

2. Alaskan Stream Volume, Freshwater, and Heat Transports

The fifteen cross sections shown in Figure 2 (AS1-AS15) were each examined for volume, heat, and freshwater transport over a twenty-five-year time period. Examining the volume, heat, and freshwater transport for section AS1 it is evident that the volume transport drives the heat and freshwater values. Volume transport through section AS1, as seen in Figure 5, remained fairly consistent to the west with a mean of ~34 Sv and net standard deviation of ~7 Sv. The maximum modeled volume transport prior to 2002 was ~50 Sv (i.e. +47%), while the minimum was observed at the

beginning of 1993 when it dropped to ~14 Sv (~i.e. -59%). Yet, in late 2002, the flow through section AS1 reversed itself, registering a net volume transport of ~-30 Sv (i.e. eastward). The monthly-averaged velocity and total kinetic energy of the region surrounding section AS1 is shown in Figure 6. In the Figure, the model depicts the ability of an eddy to drastically alter the direction of the Alaskan Stream. Similar fluctuations of Alaskan Stream transport at AS1 were also witnessed by Reed and Stabeno (1989). They observed, through data gathered from current moorings located south-west of Kodiak Island, that the Alaskan Stream had moments of negligible westward flow (April-July 1986), while at other times (1987-1988) it maintained a strong and steady flow. They theorized that this might have been due to a southward shift in the Alaskan Stream (~50 km). Considering that these reductions in the volume transport of the Alaskan Stream were only witnessed in spring 1986 and 1987, while the observed data in 1988 lacked any major deviation from the mean flow implies that there is no seasonal trend to the southward shift (Reed and Stabeno, 1989).

The modeled mean heat transport (609 TW) across AS1 (velocity*($T-T_{ref}$), referenced at -0.1^{0}C) indicates a net flux of warm water. Comparison of heat transport and volume transport plots shows them to be positively correlated, exhibiting similar prominent deviations from their respective means in 1987, 1989, 1993, and 2002.

Unlike the heat flux, the modeled net freshwater transport (velocity*(S_{ref}-S)/S_{ref}) exhibits only two prominent deviations from its mean (1993, 2002).

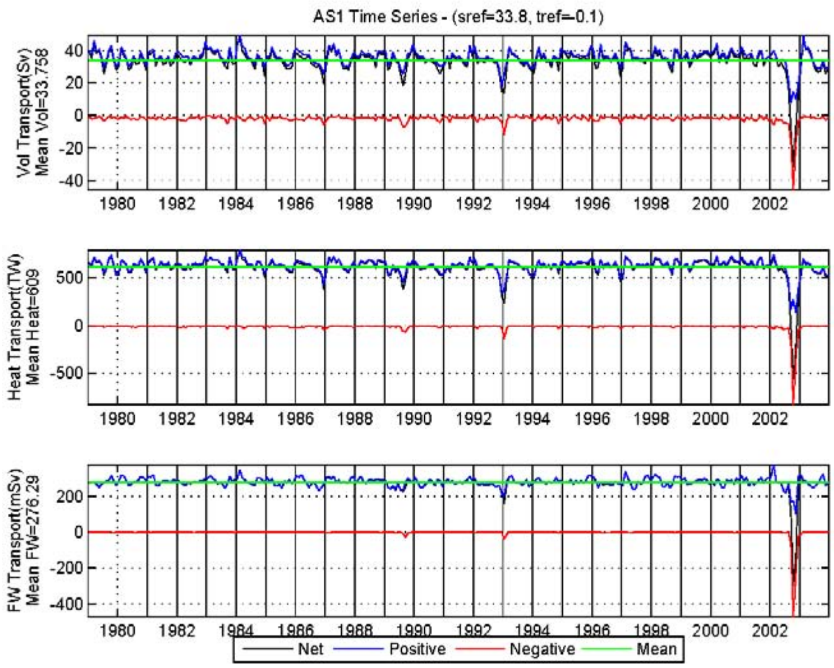


Figure 5. Section AS1 monthly mean volume, heat, and freshwater transport over a 25-year time series (1979-2003). Positive (blue line) transports represent flow to the west, while negative (red line) transports represent flow to the east. Black lines represent net flow. The 23-year mean is represented by the green line.

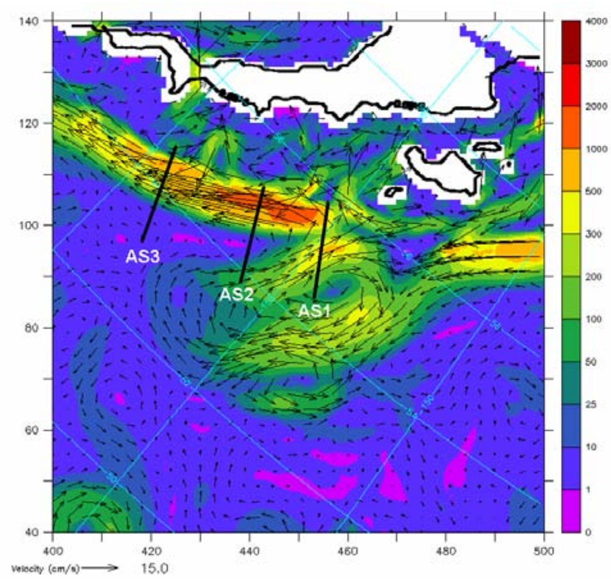


Figure 6. Mean monthly depth-averaged velocity of the entire water column during the month of highest reversal eastward at AS1 during 2002. Color shading represents the total kinetic energy ($cm^2\ s^{-2}$).

The modeled volume, heat, and freshwater anomalies were also calculated for AS1 (Figure 7). In order to compute these anomalies, the monthly average values in the annual cycle (Figure 7) were subtracted from the net volume, heat, and freshwater transports respectively. Ultimately, the anomalies show no trends during the 25-year (1979-2003) period. This could be attributed to the values associated with the annual cycle at AS1 (see Figure 8), which shows little deviation from the mean.

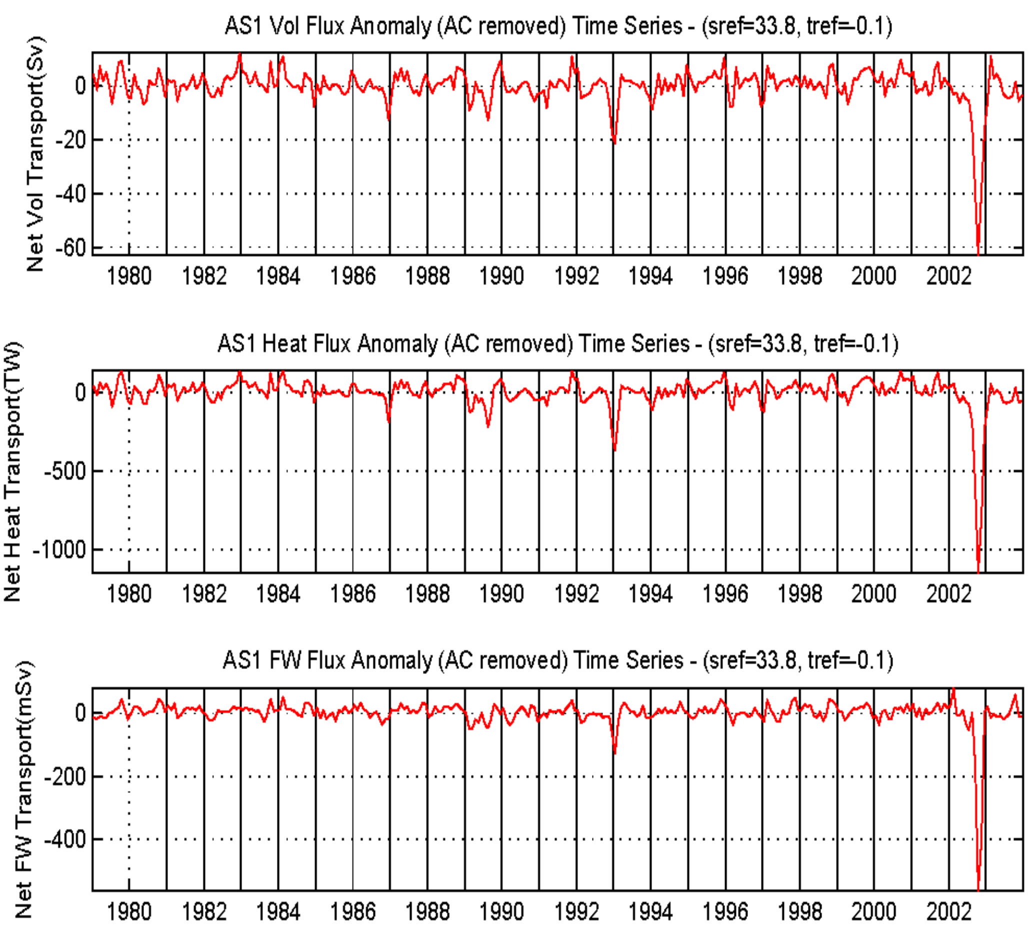


Figure 7. AS1 monthly mean volume, heat, and freshwater transport anomalies over a 25-year time period (1979-2003). Transport anomalies over the 25-year time period are calculated by subtracting the respective annual cycle fluxes from net volume, heat, and freshwater transports.

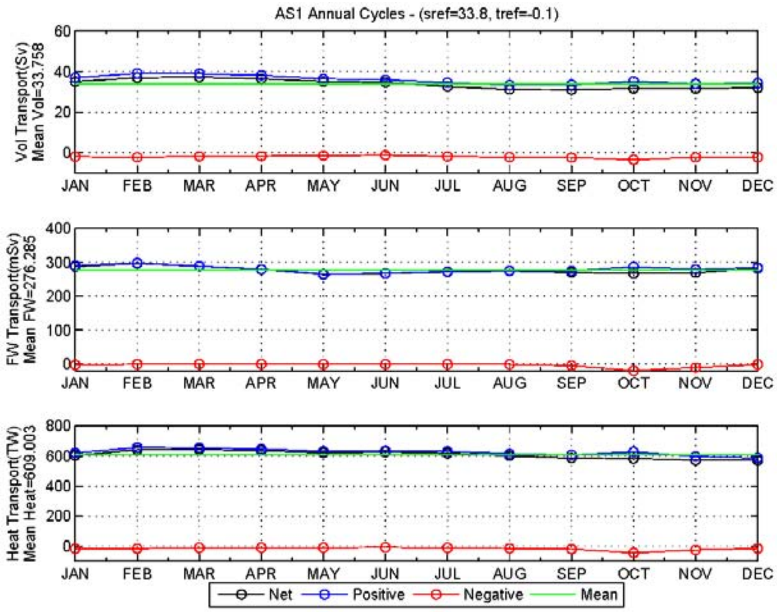


Figure 8. AS1 annual cycle volume, heat, and freshwater fluxes. Monthly means are calculated from a 25-year time series (1979-2003). Positive (blue line) fluxes represent the flow to the west, while negative (red line) fluxes represent the flow to the east. Black lines represent the net flow. The green line represents the mean flux.

The second Alaskan Stream cross section which will be examined is AS5 (see Figure 3). Located just south and upstream of Unimak Pass, time series of fluxes across this section include the flow of the Alaskan Coastal Current and possibly other waters entering the eastern Bering Sea via Unimak Pass (Figure 9). Examining the volume, heat, and freshwater transports at AS5 there is a noticeable difference in the number of peaks as compared to cross section AS1. The 25-year modeled volume transport has four significant deviations from the mean, the largest of which indicates a flow reversal of close to -9 Sv. Consequently, the increase in departures from the mean volume transport further down the stream has a significant effect on the flow of Alaskan Stream water through Unimak Pass, as discussed in section B. It is also important to note that

while there is a marked increase in the number of deviations reducing the flow of the stream at AS5, the mean volume transport increased to ~38.3 Sv (~13% increase) compared to the volume transport at AS1. This increase could possibly be due to a recirculation of the Eastward Jet near AS5. Just like AS1, the heat and freshwater flux at AS5 follows the same trend as the volume flux, which again indicates that they are both directly related to the volume transport. The mean freshwater flux remains almost unchanged (280 mSv compared to 276.3 mSv) yet the net heat flux increases similarly to volume flux (by 10.8%, to 675 TW compared to 609 TW) between AS5 and AS1.

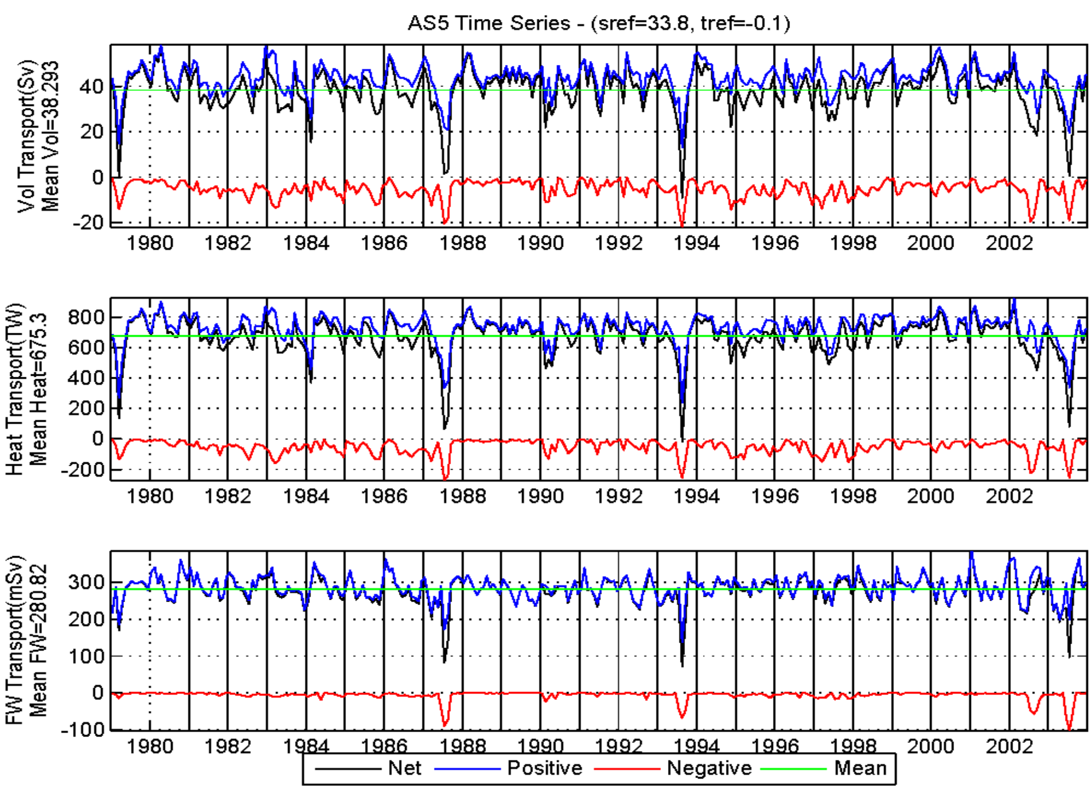


Figure 9. AS5 monthly mean volume, heat, and freshwater transport over a 25-year time series (1979-2003). Positive (blue line) transports represent flow to the west, while negative (red line) transports represent flow to the east. Black lines represent net flow. The 23-year mean is represented by the green line.

Like the previous cross sections, AS7 presents time series data that is worthy of note (see Figure 10). Firstly, the mean modeled volume transport has again increased as the cross sections move westward (to ~43.7 Sv, or by ~14% compared to the flux through section AS5). This intensification of the Alaskan Stream is believed to be due to a portion of the eastward jet (just south of the Alaskan Stream on the Aleutian Rise) diverging north, enabling the Alaskan Stream to strengthen as it moves west of AS7 as shown in Figure 4 (Maslowski et al. 2005). Another interesting feature of time series at AS7 is the reduced number of significant deviations in the volume transport as compared to volume transport at AS5. Decreasing to an average volume transport of ~20 Sv on three separate occasions (1987, 1993, and 2002) transport at AS7 averaged a drop off in flow equal to ~23.7 Sv from the mean during these three time years. This value, while significant, is far less than that at AS5, which decreased in volume transport by an average of ~39 Sv from the mean on four different occasions (1979, 1987, 1993, and 2002) during the 25-year time period (1979-2003). This change in the Alaskan Stream at AS7, towards a more consistent westward flow, may be again attributable to the re-circulation of the eastward jet. Essentially, the branch of Eastward Jet pushing water northward might restrict the Alaskan Stream from having a strong southward shift during periods of eddy propagation. Along with the considerable increase in the volume transport between cross sections AS5 and AS7 the heat transport increased to 742.5 TW at AS7 (or by ~10%), compared to 675.3 TW at AS5. Conversely, the freshwater transport remained relatively the same across the two cross sections with very little deviation from the mean.

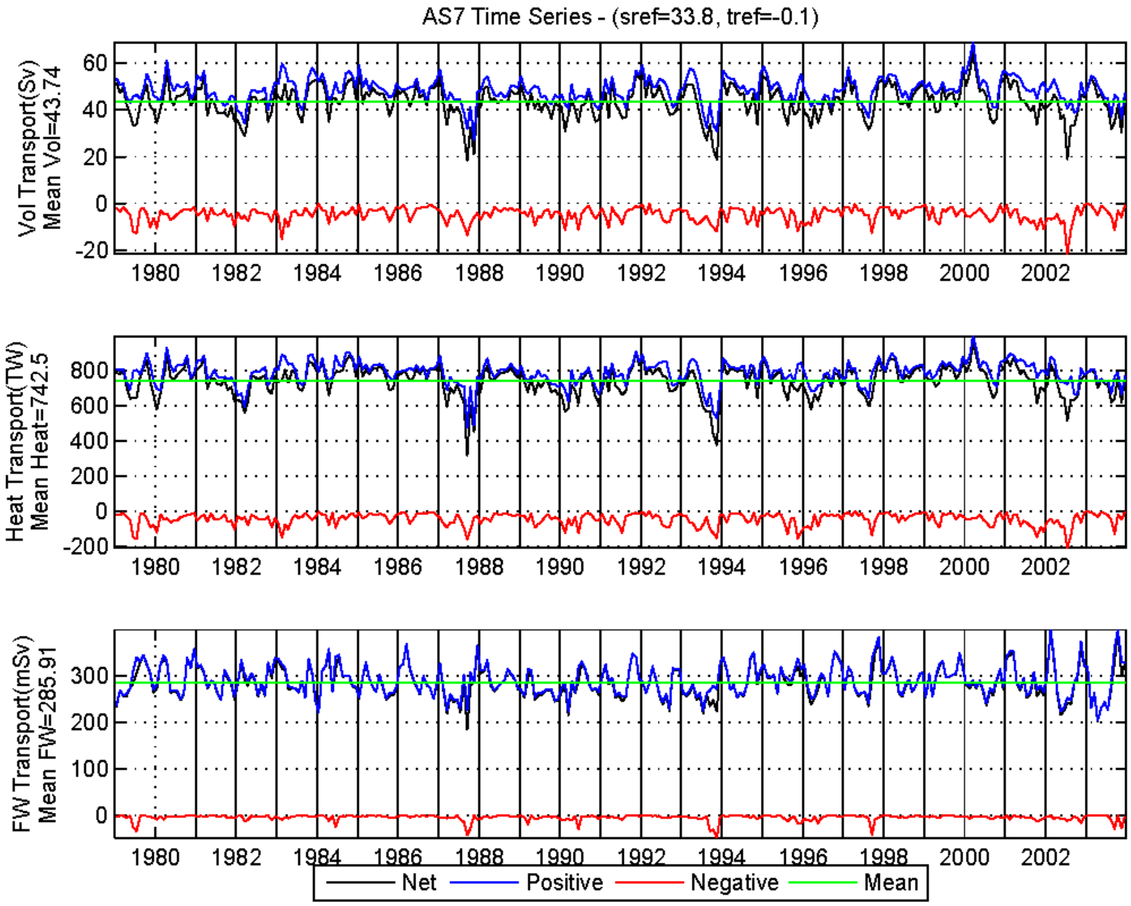


Figure 10. AS7 monthly mean volume, heat, and freshwater transport over 25-year time series (1979-2003). Positive (blue line) transports represents flow west, while the negative (red line) represents flow to the east. Black lines represent net flow. The 23-year mean is represented by the green line

AS9, as seen in Figure 2, is the next cross section examined in this chapter. Relative to the previous cross section, AS9 displays Almost no change in the mean volume transport (~44.3 Sv, or 1.4% compared to AS7), as well as an even greater propensity to deviate from the mean (see Figure 11). Reaching a reduced flow of <20 Sv on six separate occasions (1979, 1984, 1988, 1990, 1994, and 1997) AS9 displays the Alaskan Stream’s increased variability as it progresses westward. It is also important to note that

AS9 is the cross section immediately before Amukta Pass (see Figure 2). This is a critical detail, because the high variability of the volume transport at AS9 has a significant affect on the stability of flow through Amukta Pass. Unlike the large difference in the mean modeled heat transport between AS5 and AS7, there is little change among cross sections AS7 and AS9 (~6 TW difference). On the other hand, the mean freshwater flux starts to show a gradual decrease at AS9 (by ~10% compared to AS7) that will continue to decline as more cross sections are examined further west.

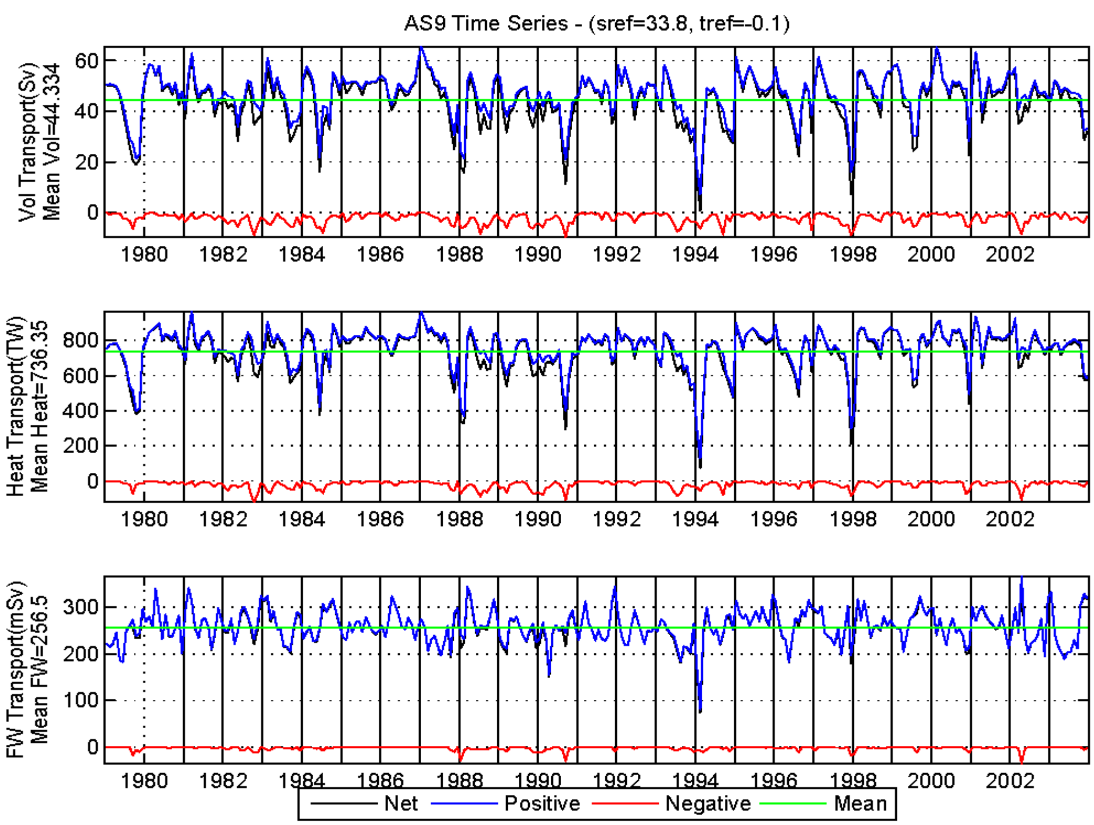


Figure 11. AS9 monthly mean volume, heat, and freshwater transport over 25-year time series. Positive (blue line) represents flow to the west, while the negative (red line) represents flow to the east. Black lines represent the net flow. The 25-year mean is represented by the green line.

AS12, AS13, and AS14 represent the most highly variable cross sections in this report. Attaining modeled mean volume transports of 43.08 Sv, 41.08 Sv, and 38.57 Sv respectively, these last three cross sections (see Figure 2) seem to indicate a gradual weakening (~13% between AS9 and AS14) of the Alaskan Stream as it progresses westward. However, further examination of Figures 12-14 reveals that it may not be a decrease in the Alaskan Stream, but rather an increase in the duration of peaks showing decreased flow, and flow reversals. Specifically, the dips seen in Figures 12-14 during 1985, 1988, 1994, and 1998 reflect significant reductions in volume transport below the mean, lasting often for more than a year. During these four time periods, the flow reversals become more pronounced. Volume transport at AS12 reaches ~-20 Sv in 1988, while during the other three time periods flow reversals reach greater than -10 Sv. AS 13 and AS14 both record a volume transport below -20 Sv on three separate occasions, while AS14 reaches its maximum flow reversal in 1998 registering ~-39 Sv. Note that cross section AS13 is located just upstream from Amchitka Pass, which is recognized as the third deepest pass in the Aleutian Island arc. Flow through Amchitka Pass helps drive both the Aleutian North Slope Current and eventually the Bering Slope Current, as well as influence the water properties within the Bering Sea. Taking this into account, significant reductions and sometimes reversals in the volume transport of the Alaskan Stream at AS13, just upstream of the pass, severely influence exchanges through Amchitka Pass.

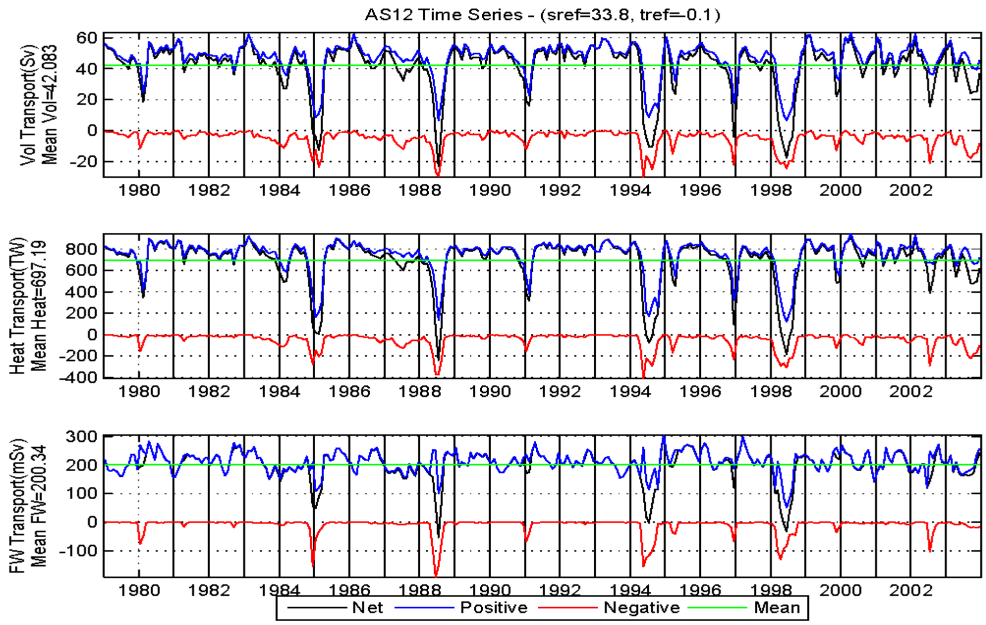


Figure 12. AS12 monthly mean volume, heat, and freshwater transport over 25-year time series. Positive (blue line) represents flow to the west, while the negative (red line) represents flow to the east. Black lines represent the net flow. The 25-year mean is represented by the green line.

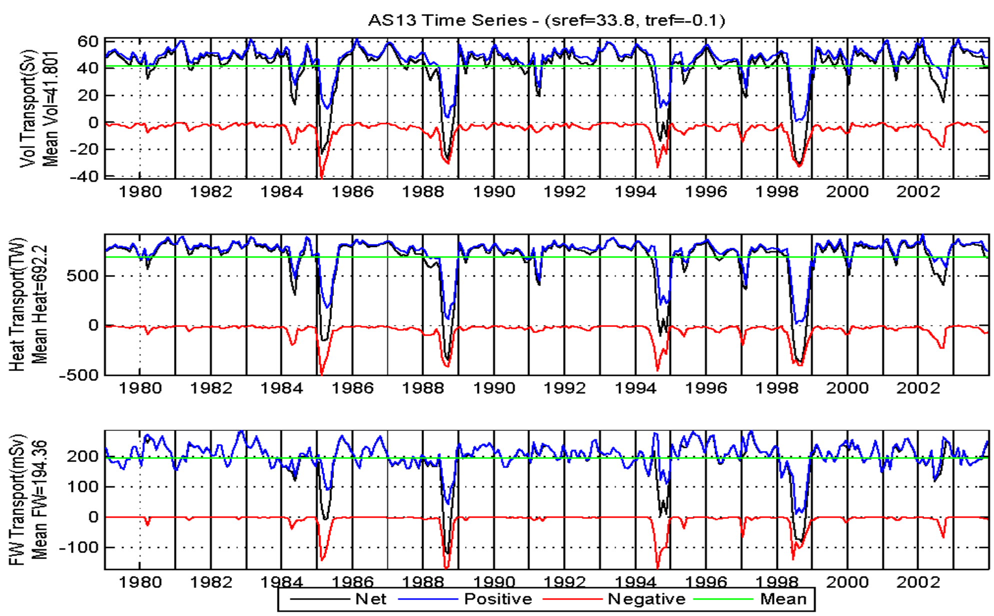


Figure 13. AS13 monthly mean volume, heat, and freshwater transport over 25-year time series. Positive (blue line) represents flow to the west, while the negative (red line) represents flow to the east. Black lines represent the net flow. The 25-year mean is represented by the green line.

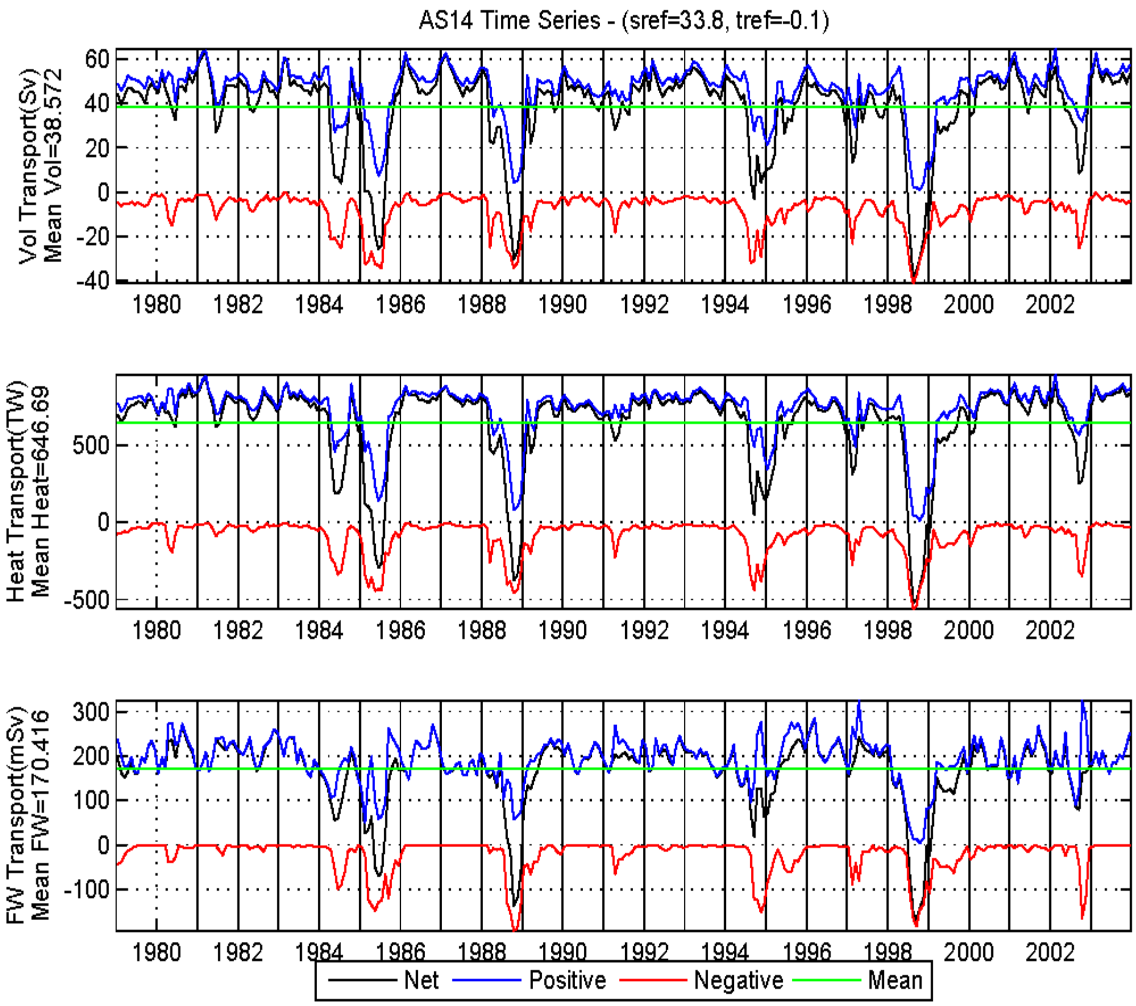


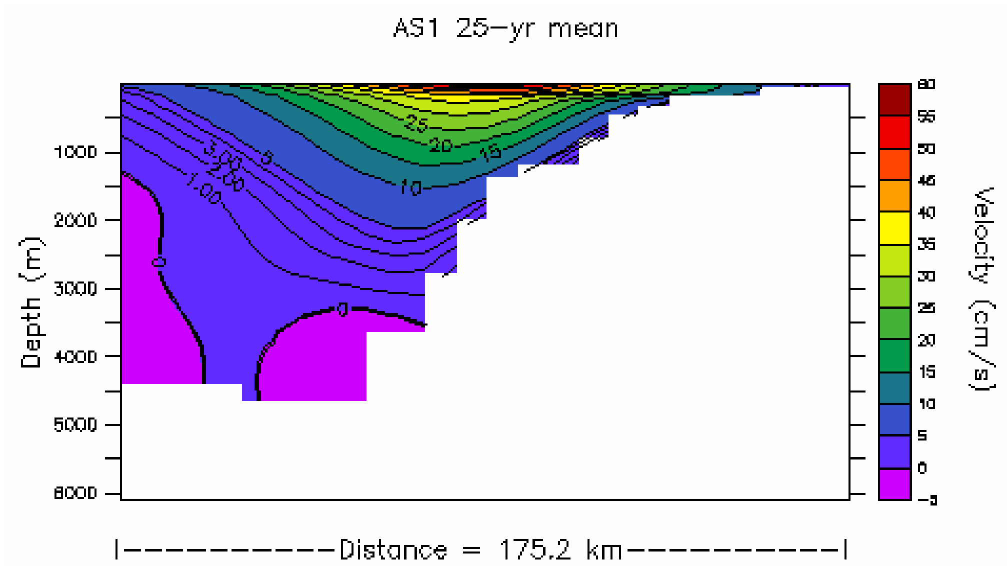
Figure 14. AS14 monthly mean volume, heat, and freshwater transport over 25-year time series. Positive (blue line) represents flow to the west, while the negative (red line) represents flow to the east. Black lines represent the net flow. The 25-year mean is represented by the green line.

Ultimately, the dips in the volume transport seen in the previous 25-year time series Figures indicate the presence of eddies propagating westward along the Alaskan Stream. Assessment of the extent of eddy effect on the Alaskan Stream and exchanges through Aleutian Island passes, with specific focus on 1993-1995 data, will be further explained in later chapters.

3. Three-Dimensional Circulation and Water Column Structure

In order to further comprehend the flow of the Alaskan Stream at the selected cross sections, an understanding of its vertical structure must be achieved. One of the major points of discussion within this section is the examination of assumption of the level of no motion, typically set between 1000 m and 1500 m depth (Maslowski et al. 2005, Roden, 1995). Generally, among the cross sections east of AS7 (the region of recirculation), the maximum 25-year mean modeled velocities for the Alaskan Stream reach ~60-70 cm s^{-1} (westward) at the surface. Further examination of the eastern vertical cross sections (AS1 and AS5) also reveals the presence of flow below the aforementioned level of no motion (see Figure 15). Extending deep into the Aleutian trench (~4500 m depth) the 25-year model demonstrates that the Alaskan Stream can reach speeds up to ~5 cm s^{-1} beyond 2000 m, and positive (westward) flow beyond 4000 m at AS1. Consequently, the examination of velocity within the Alaskan Stream beyond the typically assumed depths of level of no motion yields a significant increase in the volume transport that is often underestimated (Roden, 1995). Focusing on a monthly mean of May 1997, Figure 16 shows the velocity at AS1 as ~60-70 cm s^{-1}, and ~70-80 cm s^{-1} at AS5 (both at the surface). These values are consistent with Reed and Stabeno (1999) who measured the maximum geostrophic flow at similar locations (see Figure 17, CTD stations 1-6 and 7-14) during the same month and year. Using data from CTD stations 1-6 (located in the same general proximity as AS1) they calculated the maximum speed to be 66 cm s^{-1}, while data from CTD stations 7-14 (located

in the same general proximity as AS5) resulted in a maximum geostrophic velocity of 65 cm s^{-1} (both speeds were calculated near the surface).



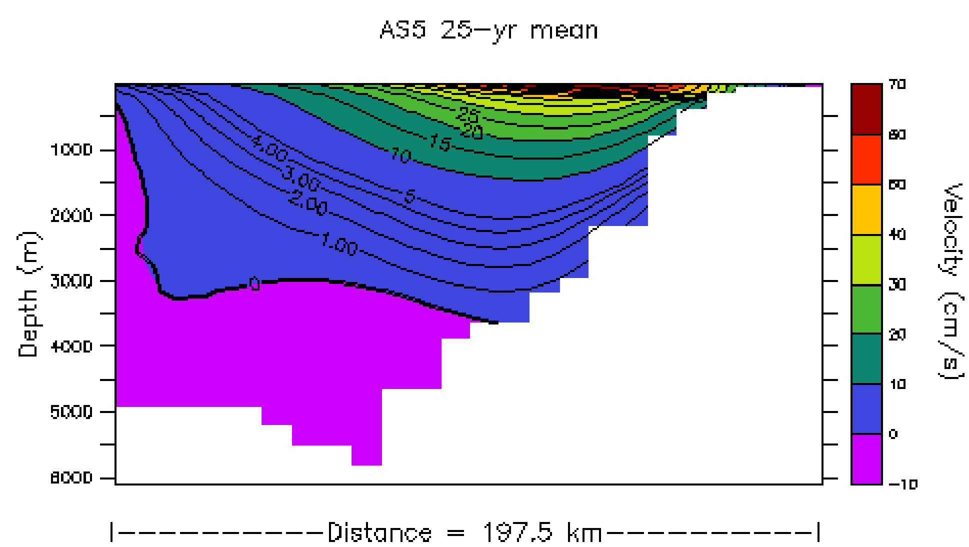


Figure 15. Twenty-five-year mean (1979-2003) profiles of velocity (cm s^{-1}) for cross sections AS1 and AS5. Positive velocity is directed westward.

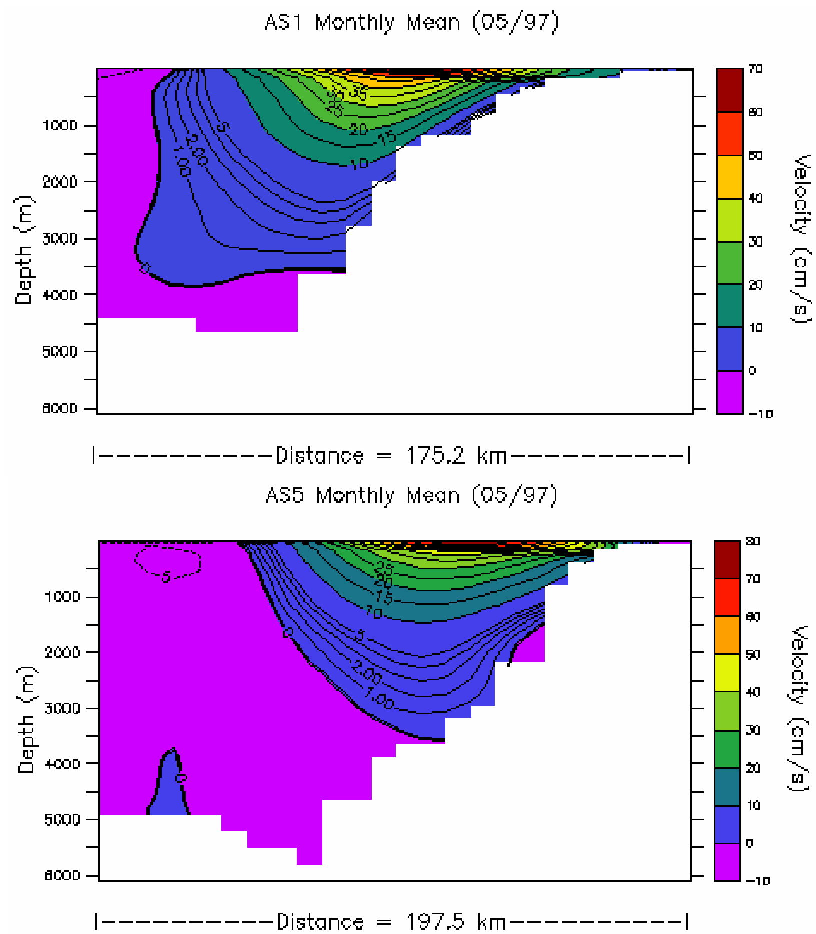


Figure 16. Monthly mean (May, 1997) profiles of velocity (cm s^{-1}) for cross sections AS1 and AS5. Positive velocity is directed westward.

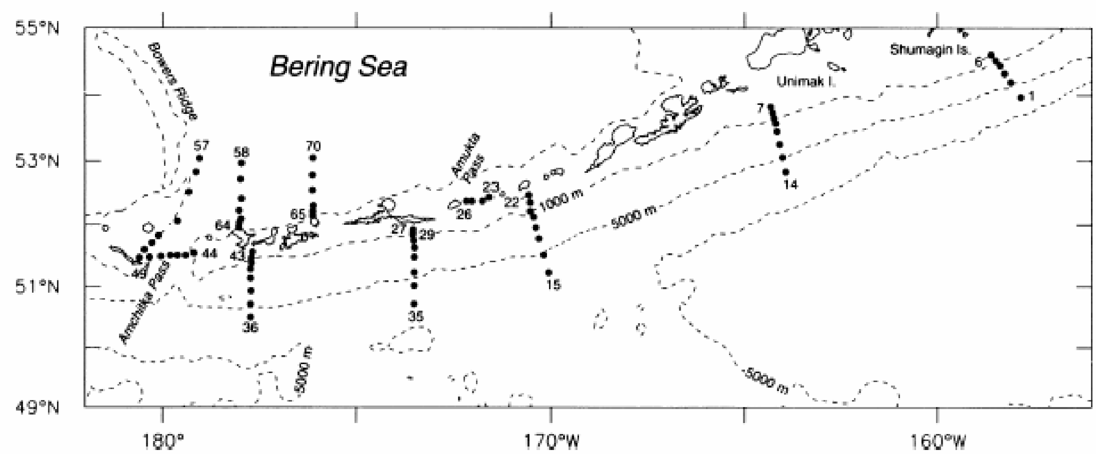


Figure 17. Location of CTD casts 18-30 May 1997. Casts were deployed to a maximum depth of 6800 m. A total of 70 casts were taken [from Reed and Stabeno, 1999].

Within the same study, Reed and Stabeno (1999) placed CTD casts just upstream (CTD casts 15-22 were located at 170^0W), and downstream (CTD casts 27-35 were located at 173.5^0W) of Amukta Pass during May 1997 (see Figure 17). Vertical velocity profiles for both CTD sections were then created, and are shown in Figure 18. In comparison to the model the two CTD sections used by Stabeno and Reed (1999) are in the same general area as sections AS9 and AS10 respectively, as seen in Figure 2. Figure 19 displays the monthly mean profiles of velocity for both sections AS9 and AS10 from the model. Comparing both Figures 18 and 19, the geostrophic velocity calculated from the May 1997 cruise data, proved to be comparable in magnitude at the location just past Amukta Pass, while the modeled velocities at the AS9 cross section differ significantly from CTD casts 15-22. In Figure 18(a) a vertical section of the geostrophic speed at 173.5^0W displays a maximum westward flow of 120 cm s^{-1} between ~80 and 210 dB, and there are significant speeds of 20 cm s^{-1} and 10 cm s^{-1} near 1200 m and 1500 m respectively. The figure also shows the Alaskan Stream extending to CTD station 34, which recorded a top speed of 10 cm s^{-1}. It is also important to note that the top speeds were all concentrated near the Aleutian Islands. Seaward of CTD station 34 an eastward flow was represented by the hatched area, marking the southern boundary of the Alaskan Stream (Reed and Stabeno, 1999). As previously discussed, the monthly mean vertical cross section at AS10 (Figure 19) displays similar trends in regards to the measured velocity as Figure 18(a). At the surface, the mean modeled velocity during May 1997 reaches a maximum of 110 cm s^{-1}, while maintaining most of its core speed near the Aleutian Island arc. At a depth of ~1300 m, the speed of the Alaskan

Stream is still significant at 20 cm s^{-1}, while the 10 cm s^{-1} contour line extends past the 1500 m mark. Unlike AS10, the vertical structure at AS9 has much less in common with the data shown in Figure 18(b). In May 1997 the model showed a maximum velocity at the surface of 110 cm s^{-1}, whereas Reed and Stabeno (1999) recorded a much weaker flow during the same time period. An explanation for such a weak Alaskan Stream could be a southward shift in its movement (away from the Aleutian Islands arc), placing most of the volume transport seaward of the CTD stations to the north.

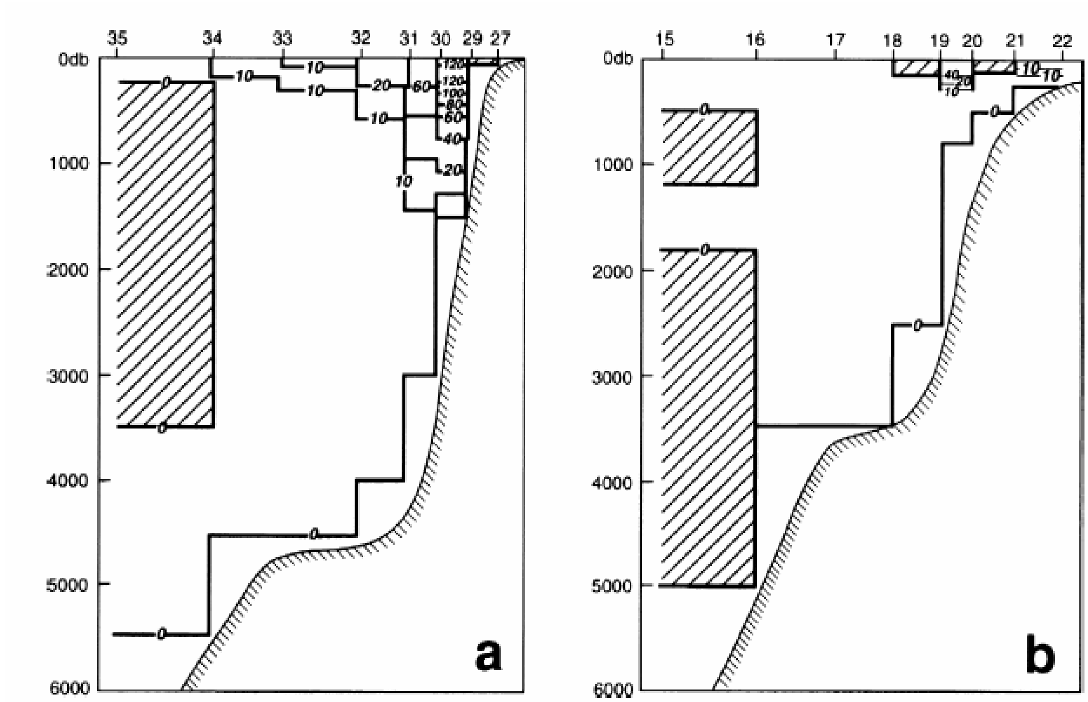


Figure 18. Vertical sections of geostrophic speed (cm s^{-1}). Figure 17(a) is located at 173.5^0W, and measured during the time period 24-25 May 1997. Figure 17(b) is located at ~170^0W, and measured during 22-23 May 1997. Hatched areas indicate eastward flow [from Reed and Stabeno, 1999]

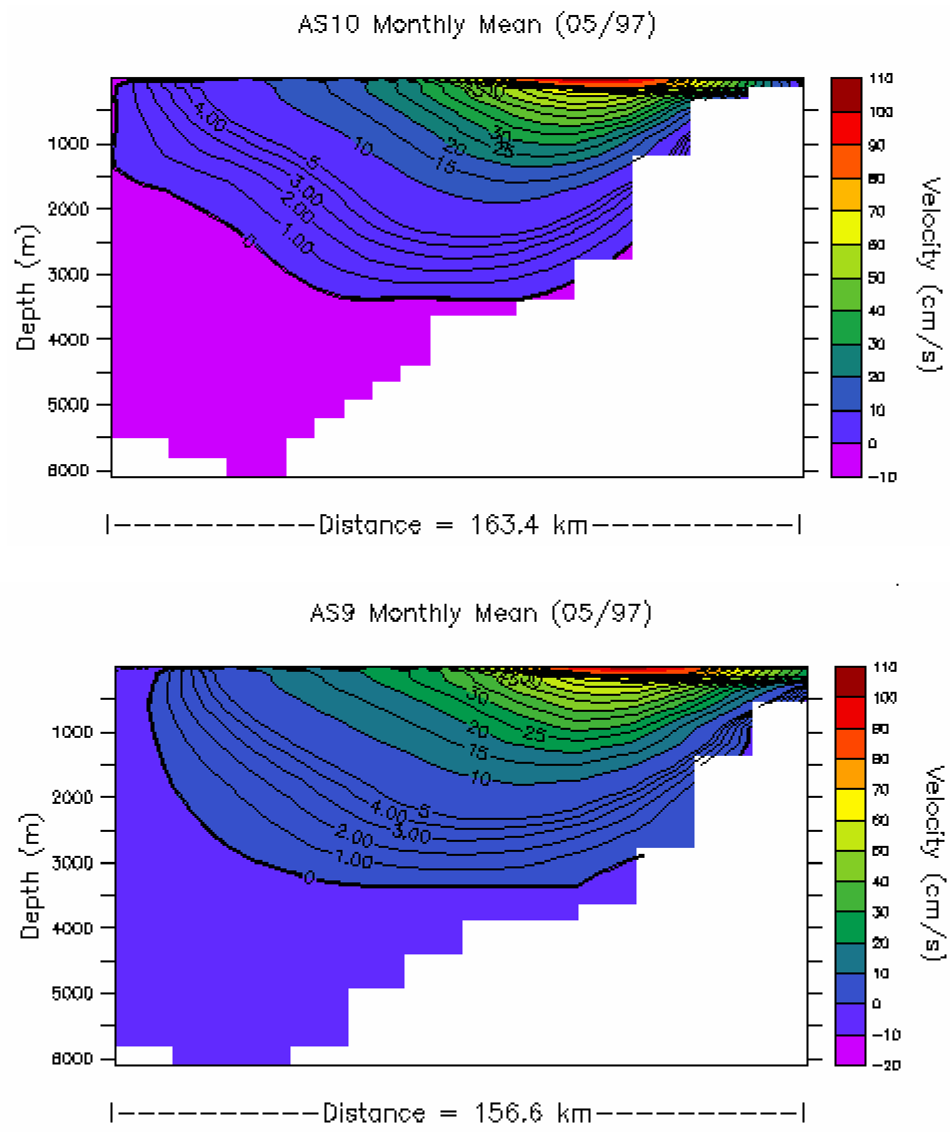


Figure 19. Monthly mean (May, 1997) profile of velocity (cm s^{-1}) for cross sections AS9 and AS10. Positive velocity is directed westward.

In order to study variability of the Alaskan Stream, and what might cause the westward flow near the Aleutian Islands to decrease (as in Figure 18(b)), it is necessary to examine the same cross section over different intensities of volume transport. Specifically, the modeled vertical cross sections of the minimum and maximum

velocities at AS10 during a one-year period (FEB 1997-JAN 1998) will be shown to demonstrate the ability of the Alaskan Stream to shift north and south. The effects of this movement on the 25-year mean profile will also be examined.

In Figure 20 (top) the vertical profile of the minimum speed at AS10 during the aforementioned time period (February 1997-January 1998) is shown. In January 1998 the speed of the Alaskan Stream was reduced to a maximum of ~40 cm s^{-1} near the surface. Along with a reduced flow at the surface, the 10 cm s^{-1} contour line only reaches a depth of 1000 m, while speeds >5 cm s^{-1} are limited to the upper 1500 m. Another distinctive feature of the Alaskan Stream during this period is the southward movement of the core away from the Aleutian Islands. Typically, the core of the westward flow is located near the Aleutian Island arc over the northern slope of the Aleutian Trench, but in this case areas of reverse (eastward) flow have replaced the typically strong Alaskan Stream near the coast. This shift in the modeled flow structure of the Alaskan Stream has been attributed to the presence of an (anticyclonic) eddy. Further investigation concerning the full effect of eddies on the Alaskan Stream will be examined in later chapters. In contrast to the vertical profile just analyzed, the modeled vertical profile of the same cross section (AS10) during the month of February (1997) depicts the maximum flow of the Alaskan Stream throughout 1997. Showing speeds of ~100 cm s^{-1} at the surface, Figure 20 (bottom) depicts the strength of the Alaskan Stream during a period of intense westward flow. Reaching a depth of 2000 m, the 10 cm s^{-1} contour line extends well below the levels of no

motion previously mentioned, and noteworthy speeds of >5 cm s^{-1} are shown to occur at depths greater than 2500 m. The most notable feature of the Alaskan Stream during this month, however, is that it exhibits positive (westward) flow throughout the entire water column.

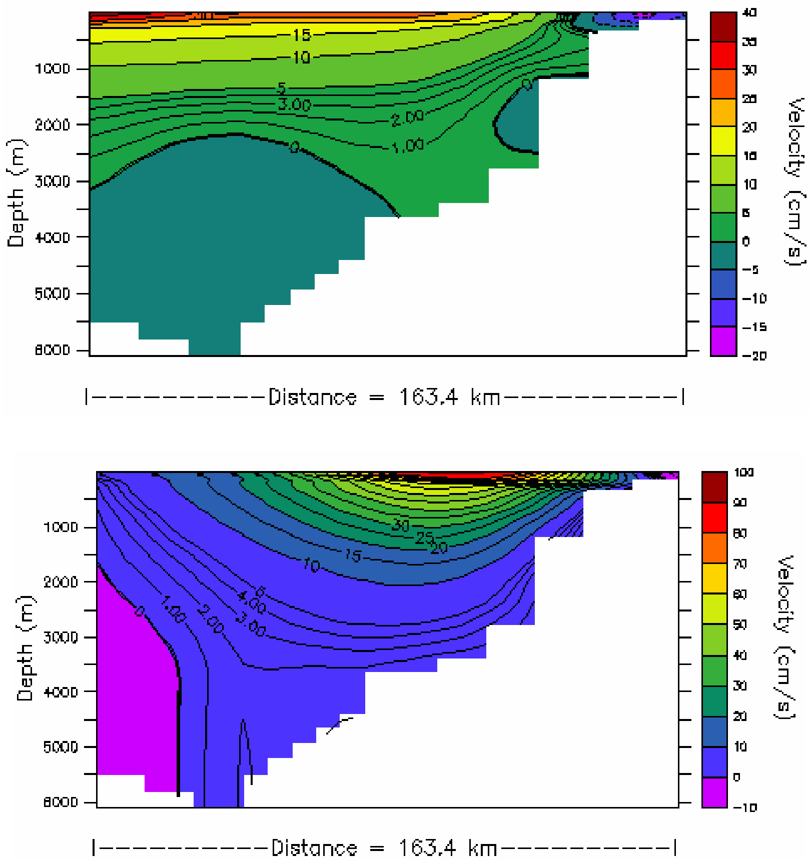


Figure 20. Monthly mean profile of velocity (cm s^{-1}) for cross section AS10 during the month of January 1998 (top), and February 1997 (bottom). Positive velocity is directed westward.

Both vertical profiles previously mentioned represent the two extremes of the Alaskan Stream during a one-year period through a single cross section (AS10). Ultimately, the variability in the location of the Alaskan Stream’s core plays an important role in the twenty-five-year (1979-

2003) mean profile of velocity (cm s^{-1}) at AS10. In Figure 21, the 25-year mean velocity structure of the Alaskan Stream is shown to exhibit a wide, westward flowing core with the 10 cm s^{-1} contour reaching ~160 km offshore. The mean width of the current at this location can be attributed to occasional southward shifts of the Alaskan Stream (as seen in Figure 20) which maintains a stronger western flow further south of the Aleutian Islands. Consequently, when averaged with other monthly means, which maintain strong flow further north, a wider overall current is produced for the twenty-five-year period (Figure 21). When measuring the mean depth of the Alaskan Stream over the twenty-five-year period, however, it is evident that the southern shifts (e.g., Figure 20, top) reduce its strength over the entire water column. In fact, over the twenty-five-year period, eastward flow dominates the lower 3000 m in the water column. The twenty-five-year mean surface speeds are reduced as well, limited to a maximum velocity of ~80 cm s^{-1}, the result of the flow reversals and periods of decreased volume transport.

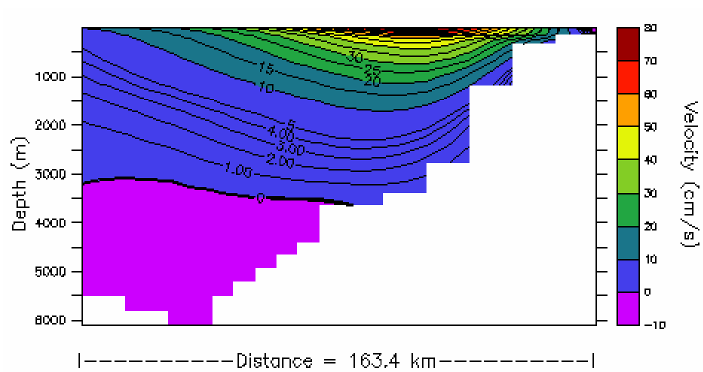


Figure 21. Twenty-five-year mean (1979-2003) profile of velocity (cm s^{-1}) for cross section AS10. Positive velocity is directed westward.

Among the middle and westernmost cross sections, specifically those west of the recirculation of the eastward jet (see Figure 4) there is a noticeable increase in the velocity of the Alaskan Stream throughout the water column. Considering AS7, the first cross section after the point of recirculation, the twenty-five-year mean velocity reaches ~80cm s^{-1} at the surface (see Figure 22). AS6, which is located just east of the region of recirculation however, displays a maximum velocity of ~60-70 cm s^{-1} (Figure 23). This is in agreement with Maslowski et al. (2005), which recognizes the recirculation of the eastward jet at AS7 as a vital element in the strength of the Alaskan Stream.

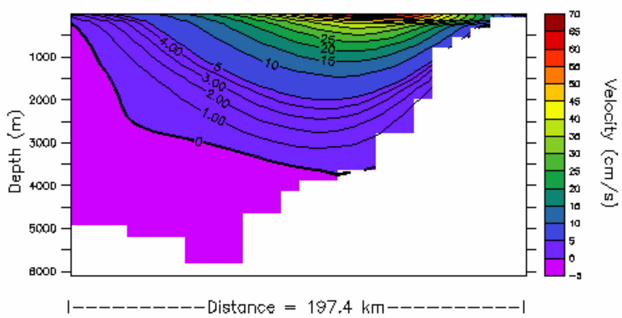


Figure 22. Twenty-five-year mean (1979-2003) profile of velocity (cm s^{-1}) for cross section AS6. Positive velocity is directed westward.

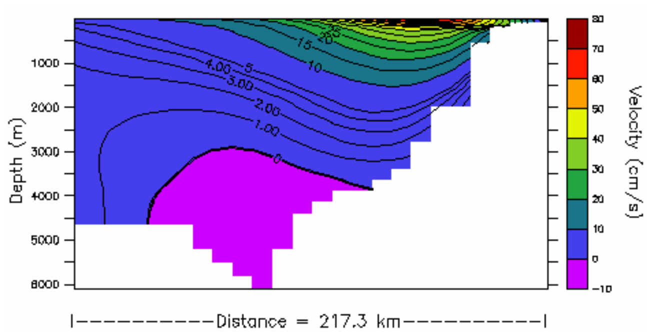


Figure 23. Twenty-five-year mean (1979-2003) profile of velocity (cm s^{-1}) for cross section AS7. Positive velocity is directed westward.

4. Eddy Effects on the Alaskan Stream During 1993-1995

The Alaskan Stream, as evidenced by the twenty-five-year (1979-2003) modeled mean circulation and kinetic energy (Figure 2), is a moderately steady current with infrequent fluctuations that can alter both its course and speed. This is in agreement with Reed and Stabeno (1989), who observed a southward movement in the current southwest of Kodiak Island in 1986 and 1987. Also, Crawford et al. (2000), examining six years of TOPEX/Poseidon (T/P) data starting in 1992, measured the presence of six anti-cyclonic eddies during September 1992 through September 1998 (Figure 24). Their surface height anomalies and diameter averaged 72 cm and 160 km respectively, while the average lifespan was one to three years. Of the six eddies, some formed near the Alaskan panhandle, while others began propagating just south of Shelikof Strait, propagating westward above the Aleutian trench. Model results also showed six eddies occurring during the 1992-1998 time period (Figure 25). Both the modeled eddies (Figure 25), and eddies observed using T/P data (Figure 24) have life-spans ranging from approximately one year to three years. Unlike Crawford et al. (2000) though, all of the six modeled eddies during this time period traveled along the Aleutian Trench until dissipating just west of Amchitka Pass.

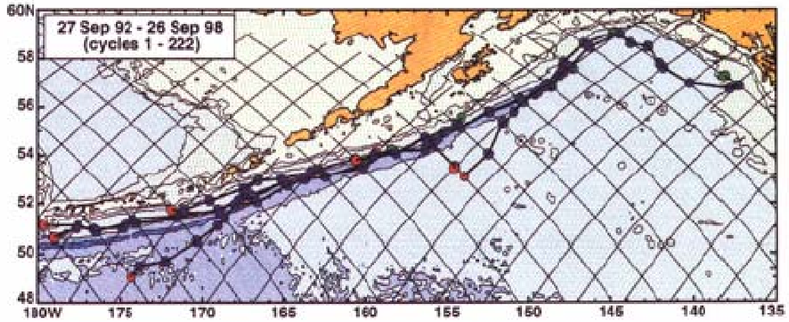


Figure 24. Trajectory of six eddies traveling along the Gulf of Alaska and into the Alaskan Stream. Tracks calculated using T/P data from September 1992 to September 1998. [from Crawford et al. 2000]

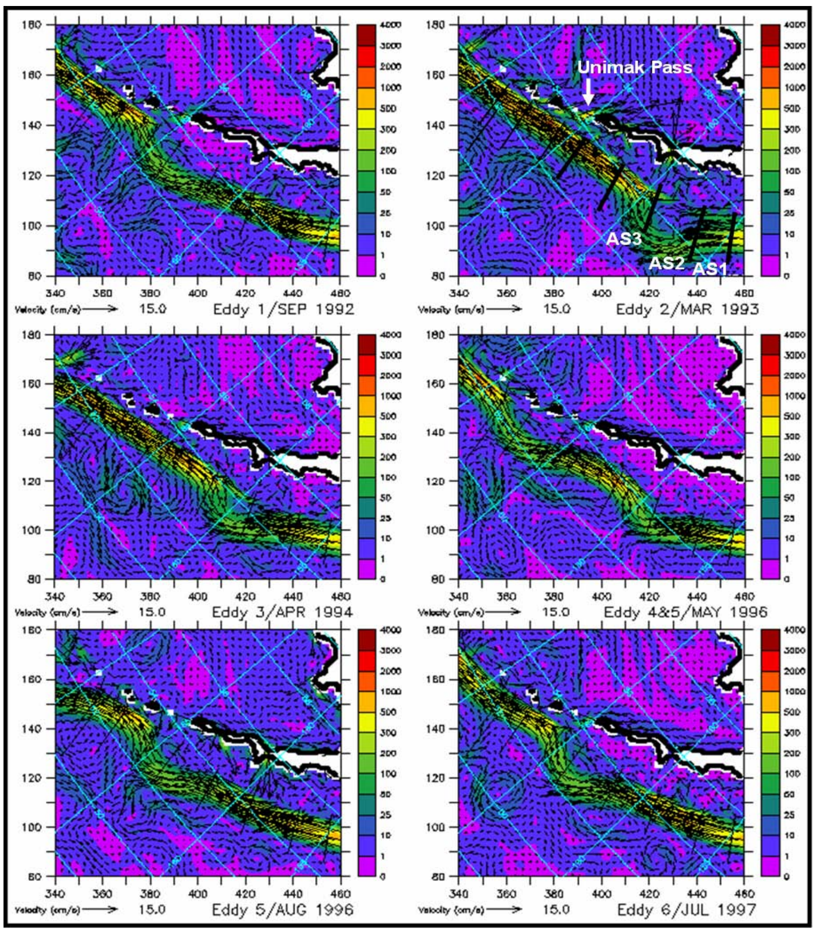


Figure 25. Modeled monthly mean velocity (cm s^{-1}) and total kinetic energy associated with six eddies propagating along Alaskan Stream during the time period September 1992 through September 1998. Color shading represents the total kinetic energy (cm^2 s^{-2}).

Eddy 2 will be explored further in this discussion, due to its visible effect on the volume transport of cross sections AS1 to AS 15 (see Figure 3 and Figure 26). The examination of Eddy 2 will begin southeast of Kodiak Island, because the area to the east of this location is beyond the scope of this report. Figure 25 shows the southward movement of the Alaskan Stream, as well as a reverse flow in the northern part of the cross section (as seen from the velocity vectors), as eddy 2 begins to pass AS3. Propagating along the Alaskan Stream, the lifespan of eddy 2 from AS1 (January 1993) until it dissipated at AS14 (April 1995) was approximately 27 months. Traveling a distance of ~1882 km during that time period, the modeled phase speed at which eddy 2 propagated westward along the Alaskan Stream was ~2.3 km day^{-1}. Again, this is in agreement with the observations made by Crawford et al. (2000) using T/P data, who estimated that the mean speeds of the six eddies witnessed during the September 1992 through September 1998 time period was 2.5 km day^{-1}. Figure 26 shows the time series (JAN 1993 - APR 1995) of volume transport at all fourteen cross sections as eddy 2 propagates from AS1 to AS14. The red vertical line on each graph identifies the lowest volume transport in each cross section as the eddy passes through. From the graphs it is apparent that the eddy is moving along the Alaskan Stream at a fairly steady pace until it reaches AS12 (exhibiting a phase speed of 3.35 km d^{-1} from AS1 to AS12), where eddy 2 begins to stall as it nears Amchitka Pass. This is evident by the increased amount of time the volume transport remains below the mean during the last three cross sections. At AS12, the modeled mean transport is 42.08 Sv, but while eddy 2 propagates through this cross section,

modeled transport falls well below the mean from April 1994 till December 1994, during which time it reached a minimum (reverse) flow of ~-10.6 Sv. Along AS13, the modeled effects of eddy 2 lasted for seven months (June 1994-January 1995), during which the minimum volume transport was ~-14 Sv. Lastly, volume transport at AS14 was below the calculated mean flow (38.57 Sv) from July 1994 until April 1995. The minimum volume transport at AS14 during this period was ~-3 Sv. The effect of eddy 2 on the Alaskan Stream at cross sections AS12 to AS14 are especially important to the northward flow through Amchitka Pass. Considering AS13 and AS14 are located just upstream and downstream from Amchitka Pass, a reduction, and sometimes reversal, of flow in the Alaskan Stream severely alters the volume transport of water entering the Bering Sea. These fluctuations in the volume transport through Amchitka Pass will be explored further in the next chapter.

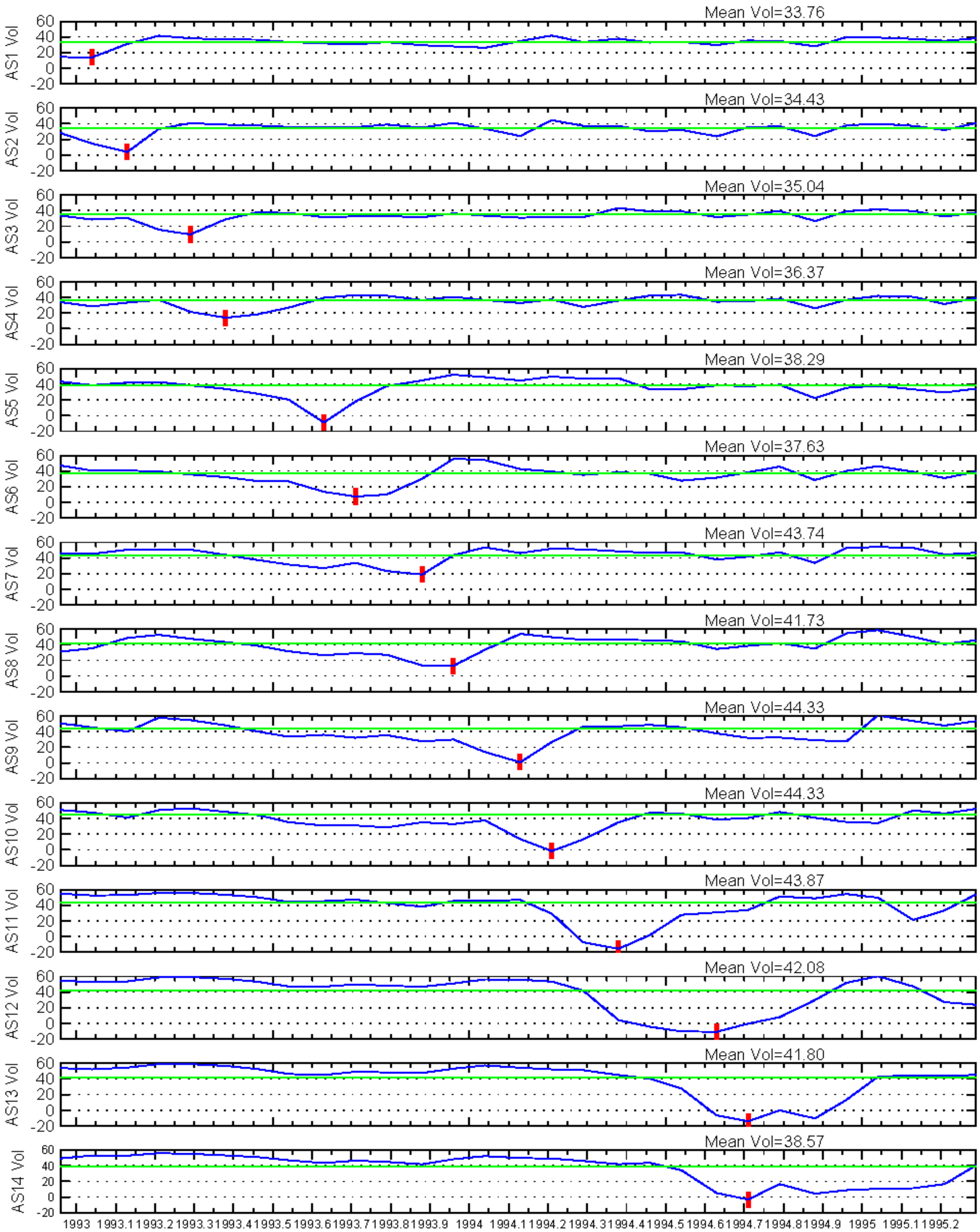


Figure 26. Monthly mean volume transport over a 27-month time series (JAN 1993 - APR1995). The blue line represents fluxes flowing west. The 25-year mean is represented by the green line. The red tick marks indicate the lowest volume transport for each cross section as the eddy passed through.

Although it has been shown that the modeled volume transport decreases as eddy 2 propagates through each of the cross sections, the speed of the Alaskan Stream remains relatively strong just south of these segments (see Figure 27). In all four monthly plots (Figure 27) the Alaskan Stream is shown to pass just south of cross sections AS2, AS5, AS9, and AS13 during the westward propagation of eddy from 1993 to 1995. Also, in most cases a reverse flow is registered at the northern end of the cross section due to the eastward flow of the anticyclonic eddy. Figure 28 depicts the mean monthly kinetic energy of the Alaskan Stream during the month of December 1993. It clearly shows not only the southward shift of the current as it passes through AS15, but also the reduced flow through the northern sections (AS7 and AS8) during the same time period. Further examination of the Alaskan Stream during December 1993 is provided in Figure 29, which is the vertical profile of AS15. With surface speeds reaching ~65 cm s^{-1} it is clear that the flow of the Alaskan Stream during the southward shifts reduces slightly, but remains relatively intact. Also, the depth of the stream during this period is remarkably strong as well, reaching speeds of ~5 cm s^{-1} at 3000m, while speeds of 3 cm s^{-1} extended to the ocean bottom (~5000 m).

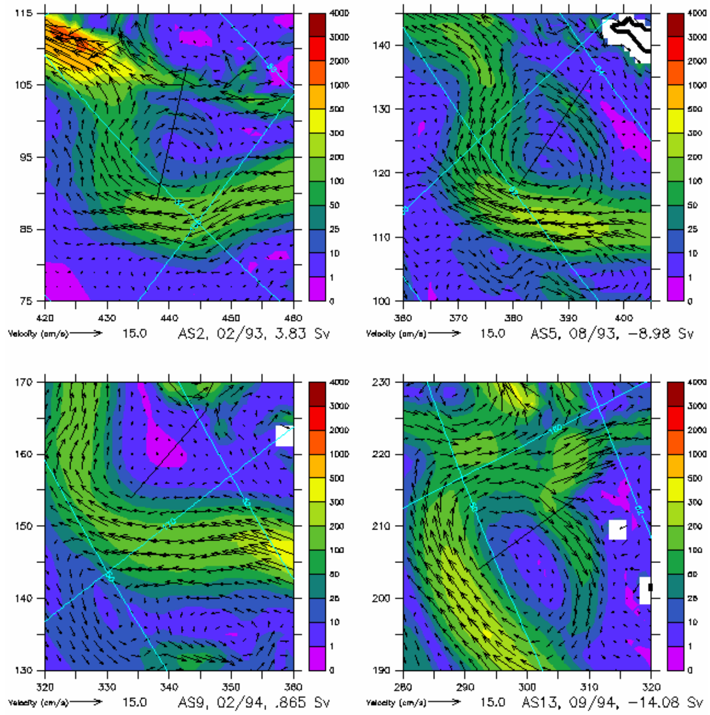


Figure 27. Mean monthly velocity and kinetic energy of the entire water column at AS, AS5, AS9, and AS13 during the month of lowest volume transport as a result of the eddy modeled from 1993-1995. Color shading represents the total kinetic energy (cm^2 s^{-2}).

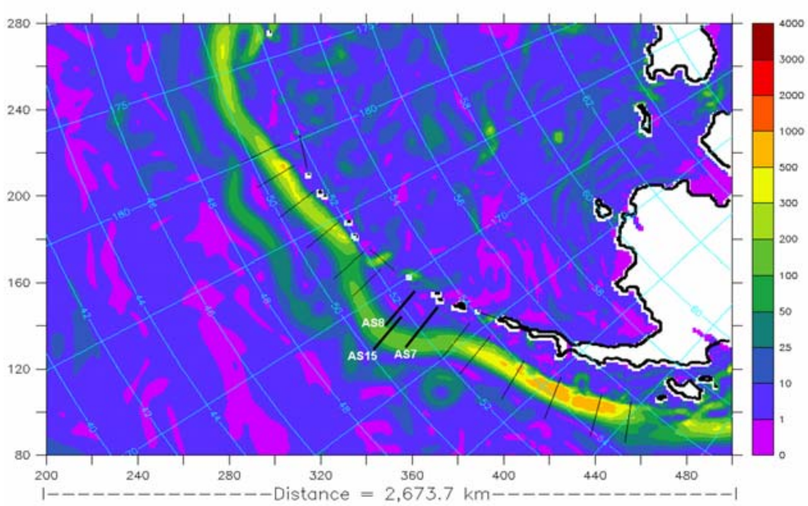


Figure 28. Mean monthly kinetic energy of the entire water column during December 1993. The southward shift of the Alaskan Stream is the result of the eddy modeled from 1993-1995. Color shading represents the total kinetic energy (cm^2 s^{-2}).

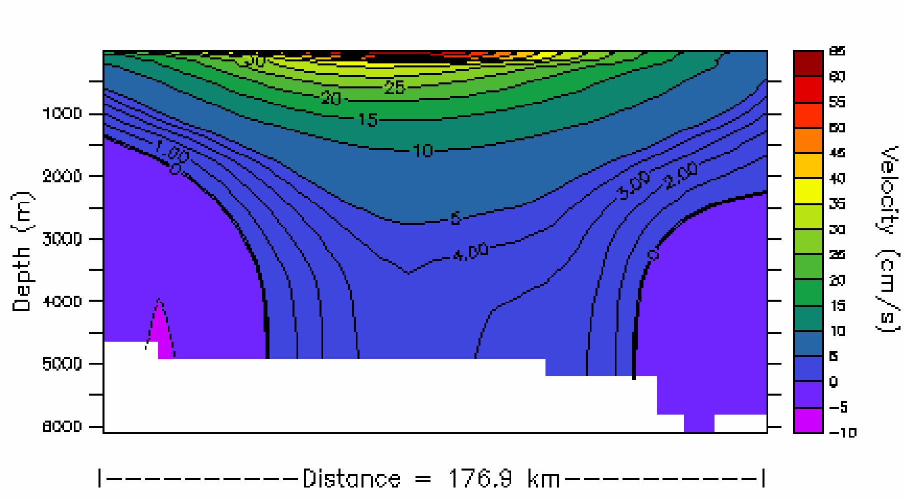


Figure 29. Monthly mean vertical profile of velocity (cm s^{-1}) for cross section AS15 during the month of December 1993. Positive velocity is directed westward.

B. THE ALEUTIAN PASSES

The Alaskan Stream, through exchanges of mass and properties across the Aleutian Island passes, has a significant impact on the circulation and upper ocean hydrography of the Bering Sea (Stabeno et al. 1999). For the purpose of this research, three passes (Unimak, Amukta, and Amchitka) are studied over a 25-year period (1979-2003). Figure 30 displays the general circulation of the westward flowing Alaskan Stream water, its northward flow through the passes, and the resultant circulation within the Bering Sea. Unimak Pass, which is a relatively narrow (~30 km wide) and shallow (average depth of ~55 m) pass, is the easternmost pass along the Aleutian Island arc (Stabeno et al. 1999, Nof and Im, 1985). While the Alaskan Coastal Current (ACC) supplies most of the water flowing through Unimak Pass, the northward flows through Amukta and Amchitka Passes are driven by the warm and relatively low salinity Alaskan Stream water (Reed and Stabeno, 1994).

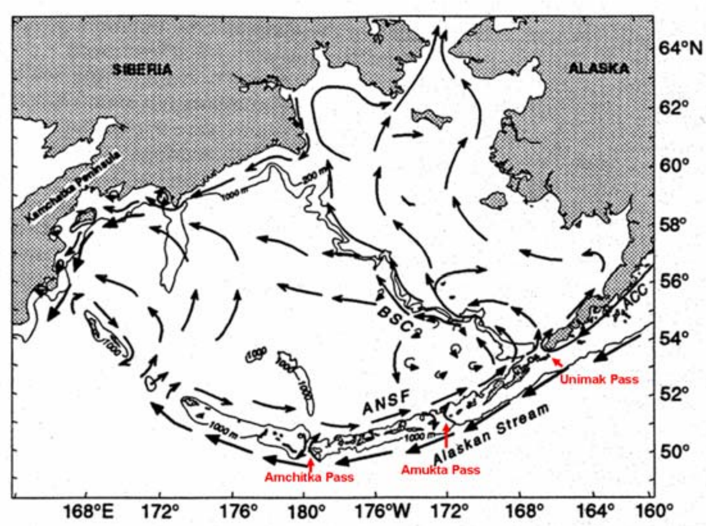


Figure 30. Schematic of the mean circulation of the Alaskan Stream and Bering Sea. Black lines represent current with mean speeds of >50 cm s-1, while the red arrows point to Unimak, Amukta, and Amchitka Pass. Aleutian North Slope Current (ANSF) and Bering Slope Current (BSC) are indicated on the map [from Stabeno et al. 1999].

1. Unimak Pass

Unlike Amukta and Amchitka Pass, very little data has been collected concerning Unimak Pass. As the easternmost passage, Unimak Pass is the main passage for ACC water moving north into the Bering Sea. Extending approximately 1000 km along the Gulf of Alaska prior to reaching Unimak Pass, the ACC is a highly seasonal current, and ultimately drives the volume transport through Unimak Pass (Stabeno et al. 2001). Figure 31 displays modeled annual cycles for the volume, freshwater, heat, and salt transport through Unimak Pass during a 25-year time period (1979-2003). Examining the annual cycle for the volume transport, it is evident that peak northward flow through Unimak Pass occurs during the winter, while the minimum is in August (summer). This is in agreement with the earlier observations that

maximum transport occurs during the winter and fall, while minimum values are observed during the summer and late spring (Stabeno et al. 1999). Also evident in Figure 31 is the fact that the volume transport drives the fluxes of other properties shown in the three lower graphs.

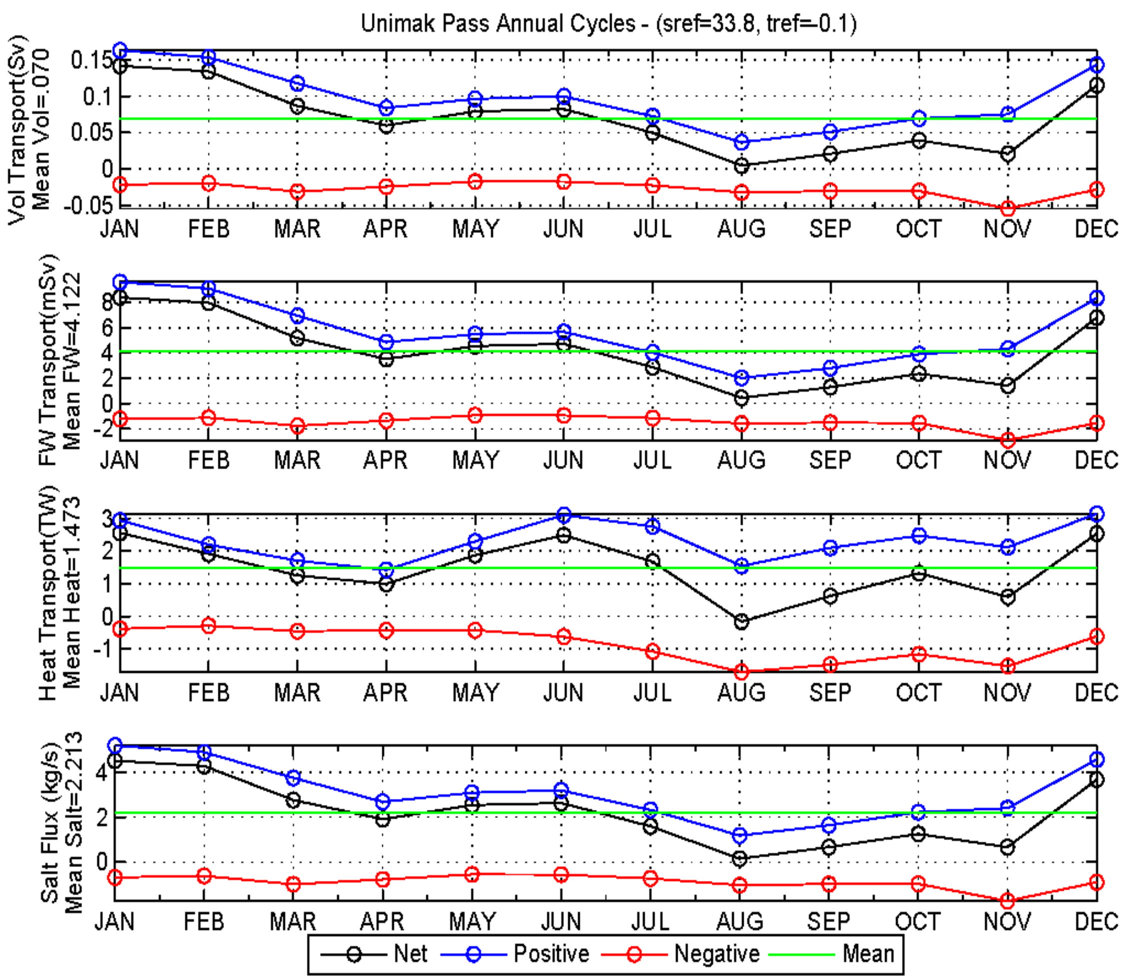


Figure 31. Unimak Pass annual cycle volume, heat, freshwater, and salt fluxes. Monthly means are calculated from a 25-year time series (1979-2003). Positive (blue line) fluxes represent the flow to the north, while negative (red line) fluxes represent the flow to the south. Black lines represent the net flow. The green line represents the mean flux.

The 25-year (1979-2003) mean transport through Unimak Pass is modeled to be 0.07 Sv (see Figure 32). It is also clear, by examining the net volume transport, that flow through Unimak Pass is highly variable. Never remaining above the mean for an entire year, the maximum transport during the 25-year period was measured to be ~3.5 Sv (1981), while it reached a net southerly flow of ~-0.2 Sv (Dec 1994). However, the net volume transport was rarely negative during the 25-year period, and the heat, freshwater, and salt fluxes exhibited similar trends. Four red asterisks are also shown in Figure 32 to identify the mean, maximum, and minimum flows through Unimak Pass during January, March, November, and December 1993, when the eddy propagated past Unimak. Figure 33 displays the velocity (cm s^{-1}) and total kinetic energy (cm^2 s^2) of the Alaskan Stream during these four months, and Unimak Pass is visible just north of the current. While the January 1993 and December 1993 Figures display flow close to the mean for Unimak Pass (0.066 Sv), March 1993 (0.188 Sv) and November 1993 (-0.123 Sv) show two different extremes as the 1993-1995 eddy propagates past Unimak Pass. First, March 1993 conditions display a strong northward flow (represented by the high kinetic energy through the eastern side of the pass), while November 1993 conditions shows no northward flow through the pass. Secondly, it is worth noting that the maximum northward flow (March 1993) occurred before the eddy even arrived at the pass, while the minimum flow was realized as the eddy was downstream of the pass.

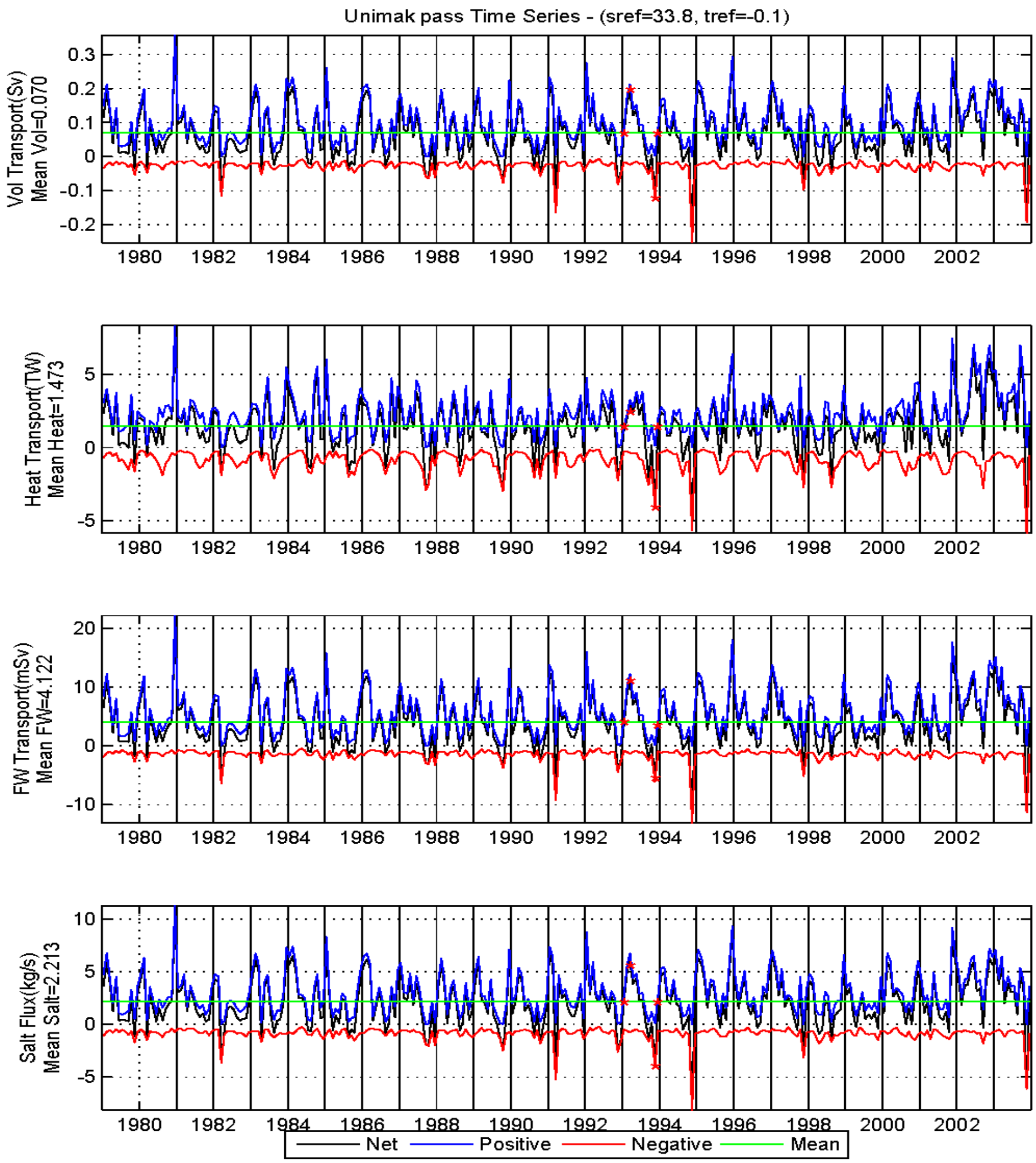


Figure 32. Unimak Pass monthly mean volume, heat, freshwater, and salt transport over a 25-year time series (1979-2003). Positive (blue line) transports represent flow to the north, while negative (red line) transports represent flow to the south. Black lines represent net flow. The 25-year mean is represented by the green line. The four red asterisks are also shown in Figure 32 to identify the mean, maximum, and minimum flows through Unimak Pass during January, March, November, and December 1993 when the eddy propagated past Unimak.

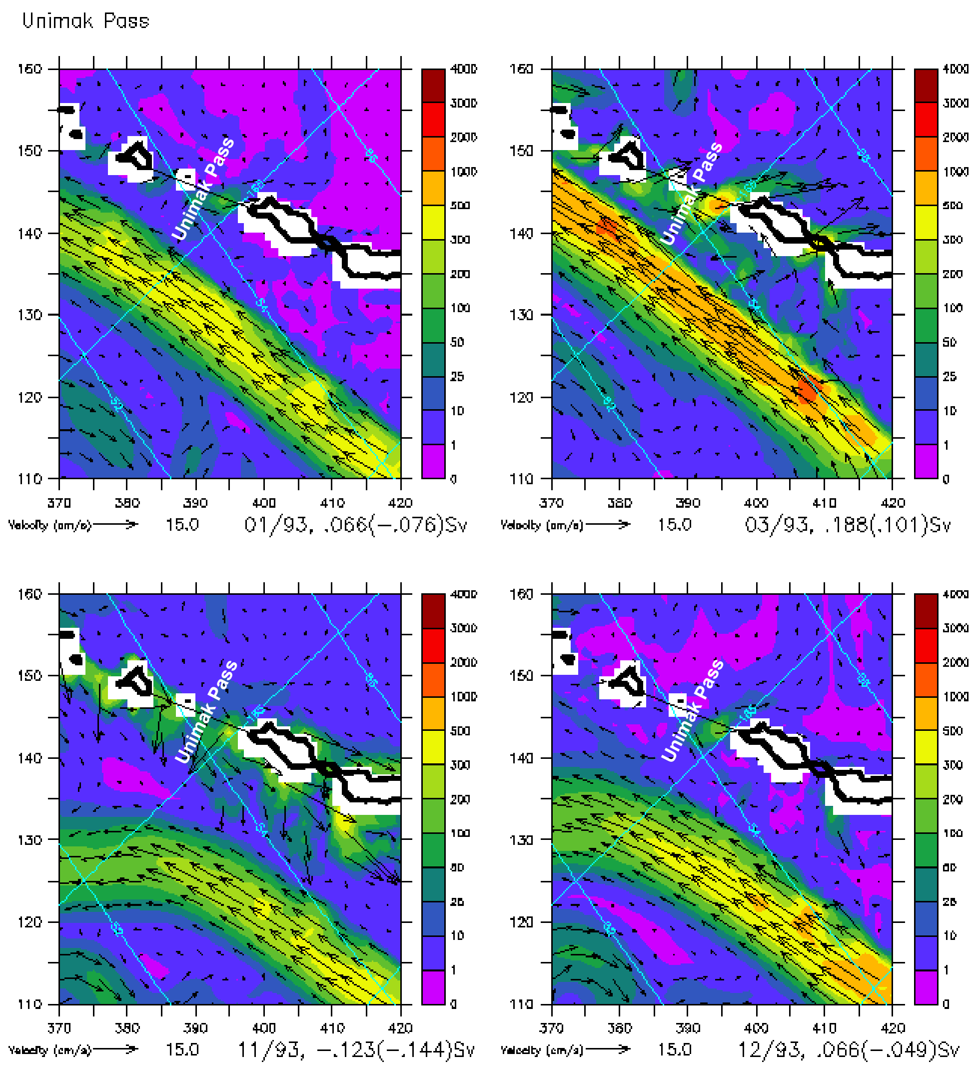


Figure 33. Mean monthly velocity (cm s^{-1}) and kinetic energy of the entire water column near Unimak Pass during the months of January, March, November, and December 1993. The volume transport in parentheses indicates the volume transport anomaly during the same month. Color shading represents the total kinetic energy (cm^2 s^{-2}).

The vertical sections across Unimak Pass reveal the distinct water properties exchanged between the Gulf of Alaska shelf and the eastern Bering Sea. It is clear, by looking at Figure 34, that the water traversing through Unimak Pass is not only fresher (maximum modeled salinity of ~32 psu), but relatively warm as well (maximum modeled

temperature of 8^{0} at the surface). It is also worth noting that flow through Unimak Pass greatly influences water properties of the eastern Bering Sea shelf (see Figure 30) which with some modifications along the way, ultimately travels northward through the Bering Strait (Stabeno et al. 1999). Lastly, the mean vertical velocity profile in Unimak Pass depicts mostly a northward flow with a small net southward flow in the west.

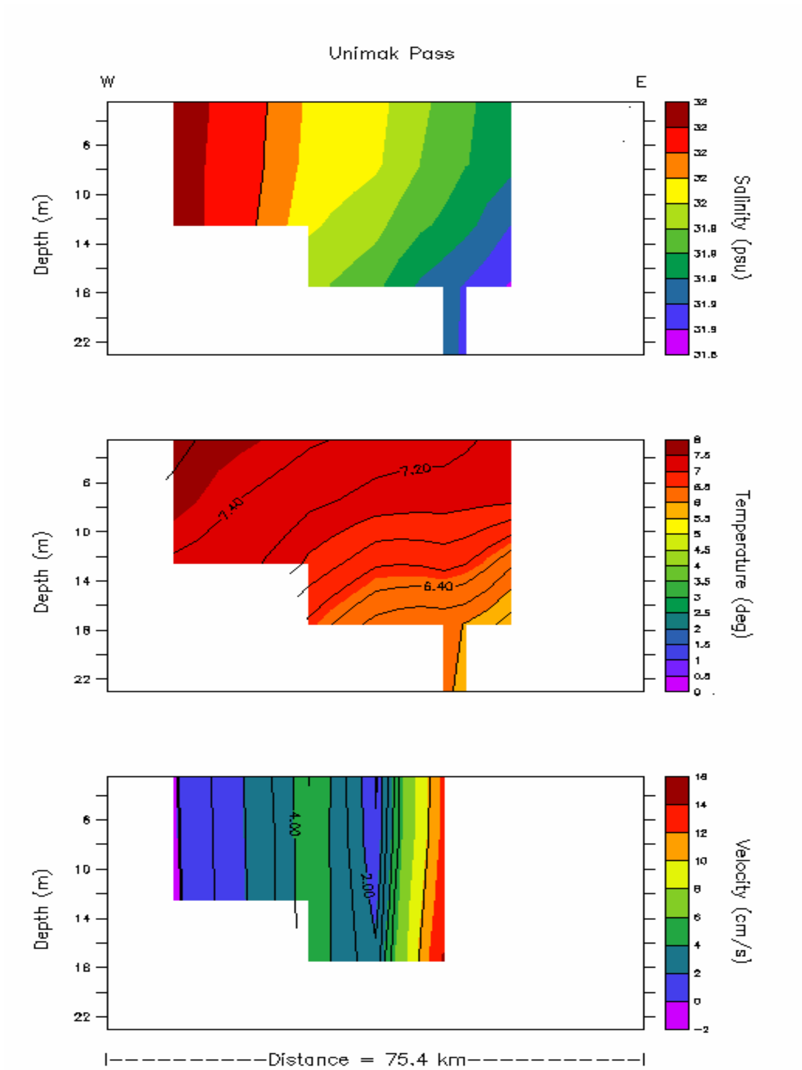


Figure 34. Twenty-five-year mean (1979-2003) profile of salinity (psu), temperature (deg), and velocity (cm s^{-1}) for Unimak Pass. Positive velocity is directed northward.

2. Amukta Pass

Amukta Pass is the easternmost major passage between the North Pacific Ocean and the Bering Sea (Stabeno et al. 1999). Like the observations by Reed and Stabeno (1994 and 1997), the 25-year model results showed variable volume transport throughout the time period (1979-2003). Ranging from a maximum of ~5 Sv (northward flow) to a minimum of ~ -1.9 Sv (southward flow) the modeled mean transport for the 25-year period is ~1.6 Sv (see Figure 35), which is significantly more variable than measurements made by Stabeno et al. (1999), who measured a maximum northward flow of 1.4 Sv, and a southward flow of <0.1 Sv. Although considered highly variable, volume transport through Amukta Pass, unlike Unimak Pass, can remain above and below the 25-year mean for periods longer than one year. Also, the effects of eddies propagating just south of the pass seem to result in longer duration changes in the volume transport. The six asterisks in each graph of Figure 35 identify different volume transports associated with the westward propagation of the 1993-1995 eddy and a follow-on eddy just south of Amukta Pass. Plots of velocity vectors and eddy kinetic energies in the Amukta Pass region at times indicated by the six asterisks are shown in Figure 36. The September 1993 plot depicts flow through the pass during mean conditions (~1.67 Sv), while December 1993, March 1994, and June 1994 plots illustrate the local effects associated with the upstream approach and ultimate passage of the eddy beyond Amukta Pass. At its peak, northward flow during the 1993-1995 eddy was modeled to be 2.88 Sv (December 1993), which is ~1.28 Sv greater than the

mean. During November 1994 minimum (southward) flow occurred as the 1993-1995 eddy has moved further west, while another, less significant southward shift in the Alaskan Stream appears just south of Amukta Pass. The total volume transport during this period is measured to be -0.19 Sv (November 1994). Like at Unimak Pass, the fluxes shown in the lower three graphs (heat, freshwater, and salt flux) follow the variability pattern of the volume transport. In the case of the heat transport, a southward shift in the Alaskan Stream, resulting in a decrease in volume transport through Amukta Pass, results in less heat being transferred northward into the Bering Sea.

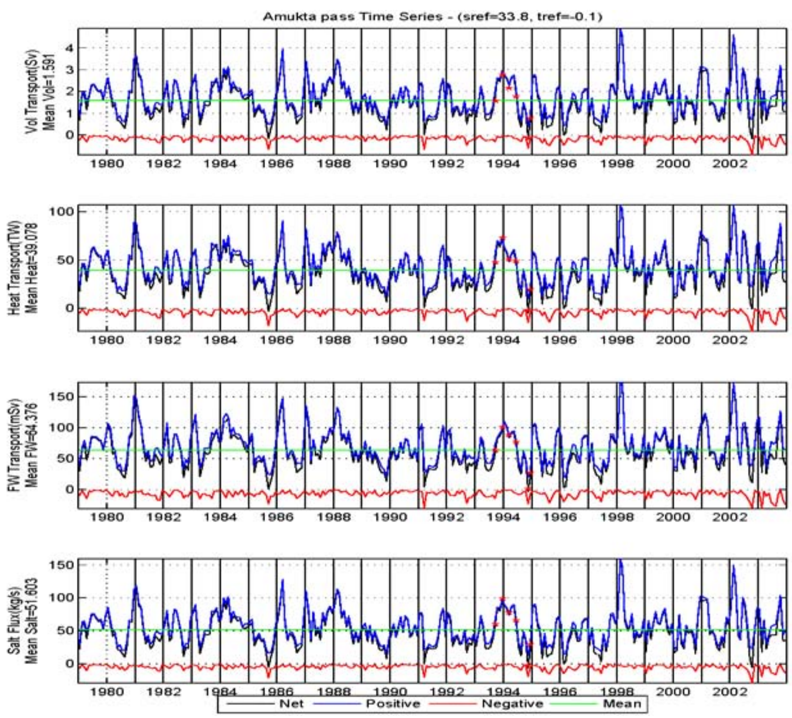


Figure 35. Amukta Pass monthly mean volume, heat, freshwater, and salt transport over a 25-year time series (1979-2003). Positive (blue line) transports represent flow to the north, while negative (red line) transports represent flow to the south. Black lines represent net flow. The 25-year mean is represented by the green line. The six asterisks identify different volume transports associated with the westward propagation of the 1993-1995 eddy and a follow-on eddy just south of Amukta Pass.

Amukta Pass

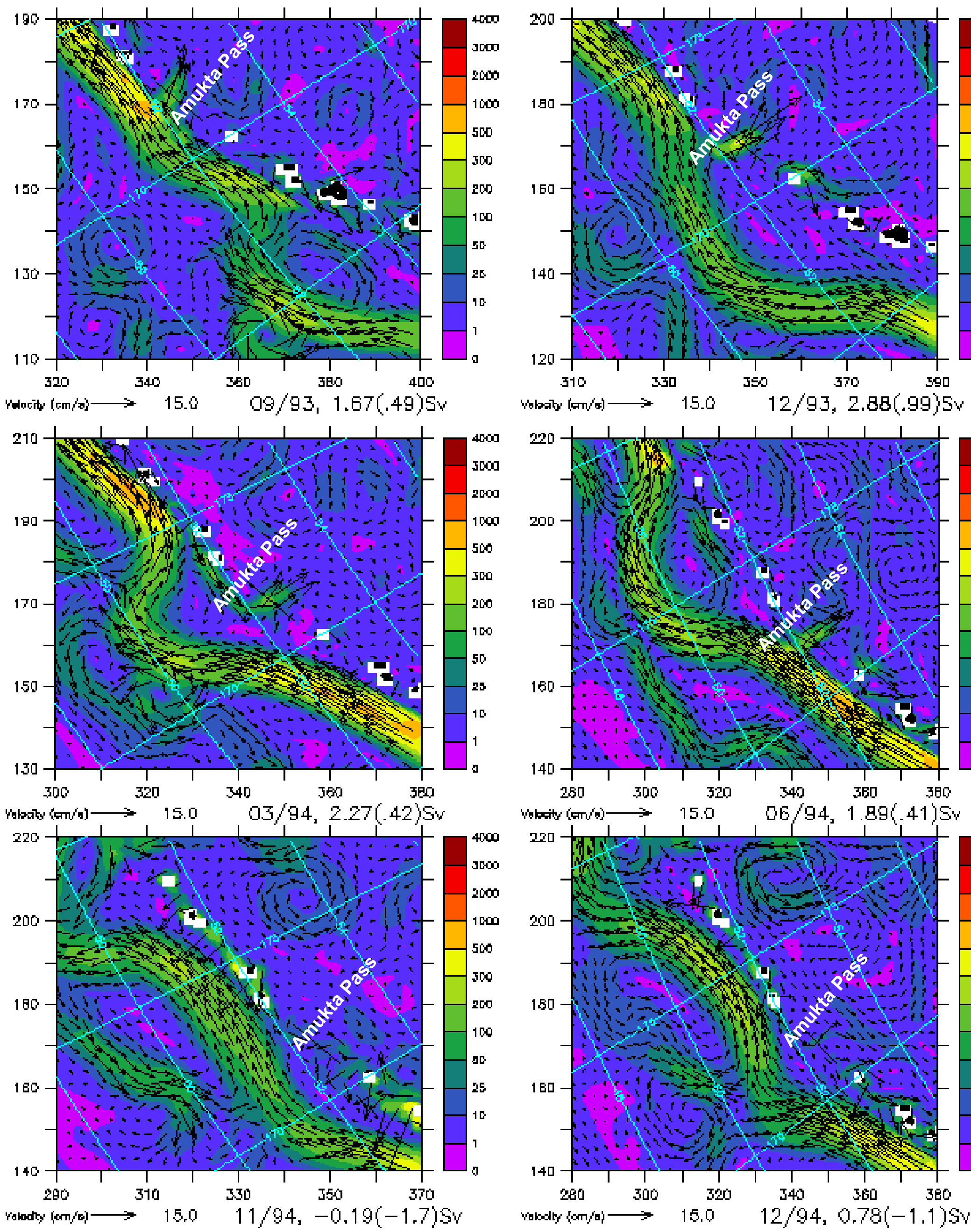


Figure 36. Mean monthly velocity (cm s^{-1}) and kinetic energy of the entire water column near Amukta Pass during six months in 1993. The volume transport in parentheses indicates the volume transport anomaly during the same month. Color shading represents the total kinetic energy (cm^2 s^{-2}).

The mean vertical salinity and temperature profiles across Amukta Pass (Figure 37) indicate a shift from the extremely low salinity and high temperature levels seen in Unimak Pass. The surface temperatures of Amukta Pass reach a maximum of ~8^0, yet contour lines for temperature above 6^0 are relegated to the top of the water column. Salinity levels reach a maximum of 33.8 psu, while salinities at Unimak Pass did not exceed 32 psu. Also, currents on the west side of Amukta Pass achieve a maximum speed of 18 cm s^{-1}, while the 10 cm s^{-1} contour line extends all the way to the ocean floor. The vertical velocity profile also distinguishes a negative flow on the eastern side of the pass. Observations made by Stabeno et al. (1999) though state that the northward flow through Amukta pass is actually on the eastern side of the pass, while southerly flow is on the west (sometimes occurring due to a re-circulation of Bering Sea water around Seguam Island). This northward flow will ultimately influence the Aleutian North Slope Current (Maslowski et al. 2005; Stabeno et al. 1999). The reason for this discrepancy in the model output is attributed to the representation of bathymetry and properties of the Alaskan Coastal Current at the pass. Ultimately, a model with increased resolution and more accurate bathymetry might resolve this issue (Clement, 2005).

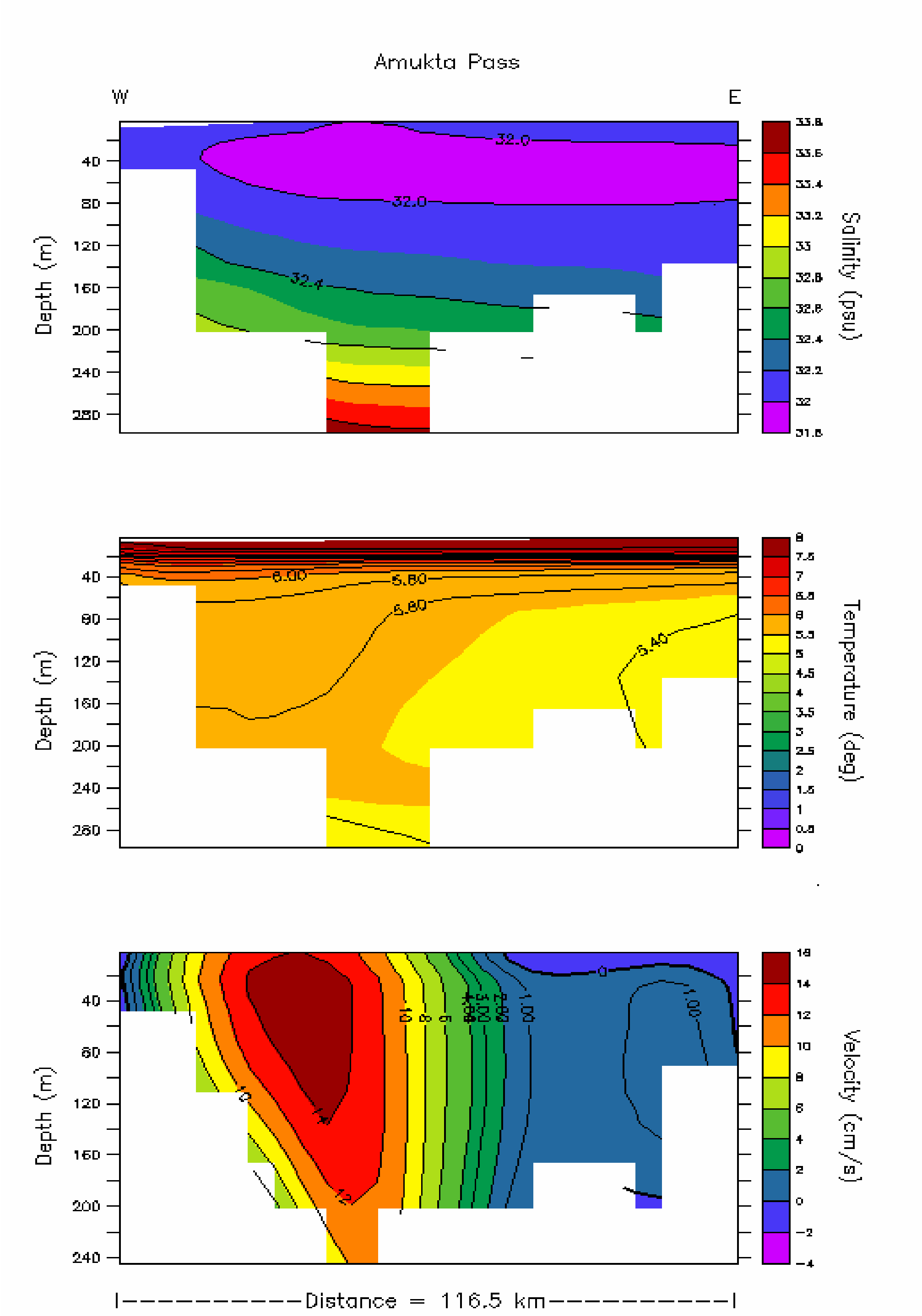


Figure 37. Twenty-five-year mean (1979-2003) profile of salinity (psu), temperature (deg), and velocity (cm s^{-1}) for Amukta Pass. Positive velocity is directed northward.

3. Amchitka Pass

Of the three eastern passes examined in this study Amchitka Pass is the largest. Located in the central Aleutian Island arc (~180^0 W), Amchitka Pass, like Amukta Pass, helps drive the Aleutian North Slope Current, which feeds the Bering Slope Current. Although the volume transport displayed in Figure 38 is variable, mean transport is modeled to be ~1.886 Sv northward. Reed (1990) made a similar calculation using CTD data during a one-year period (1987-1988) in which the net northward transport was measured to be ~1.8 Sv. Noticeable differences in the volume, heat, freshwater, and salt fluxes through Amchitka Pass, as compared to those through Unimak Pass and Amukta Pass, are the increased duration and magnitude of the deviations from the mean. Looking at the 25-year (1979-2003) volume transport time series, a maximum of ~11.5 Sv is observed in early 1985, while a minimum (reverse) flow of ~-3.4 Sv is observed in November 1996. Three periods in particular (1985 to mid-1986, mid-1994 to 1996, and mid-1998 to mid-2000) display significant increases in volume transport during the 25-year period. The mid-1994 to 1996 period of increased flow, represented by the first five asterisks, is associated with the passage of the above mentioned eddy (1993-1995), while the decrease (reverse flow) in volume transport immediately afterwards (1996-1997) is attributable to a second eddy, and is represented by the last three asterisks.

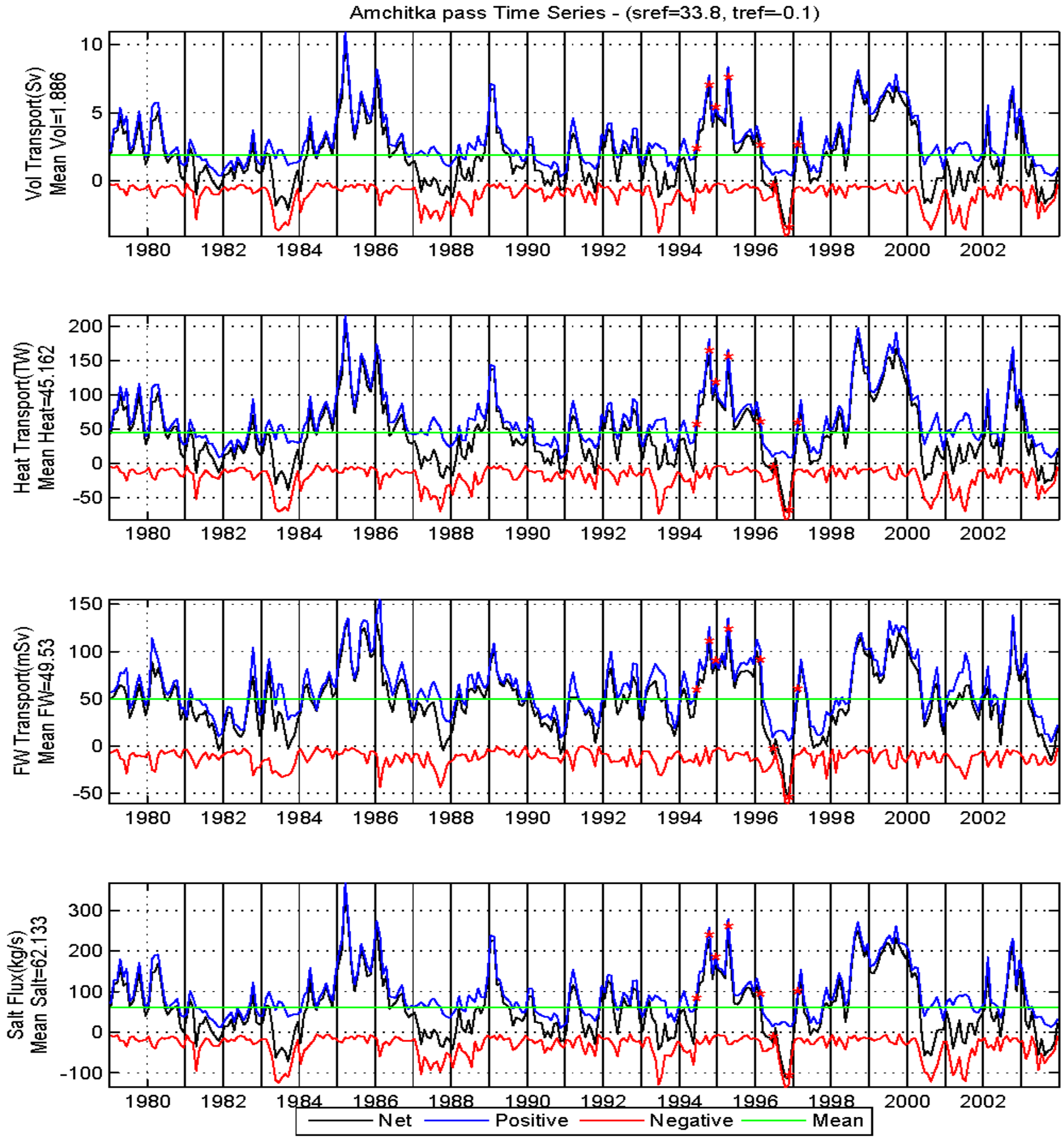


Figure 38. Amchitka Pass monthly mean volume, heat, freshwater, and salt transport over a 25-year time series (1979-2003). Positive (blue line) transports represent flow to the north, while negative (red line) transports represent flow to the south. Black lines represent net flow. The 25-year mean is represented by the green line. The eight asterisks in each graph of Figure 38 identify different volume transports associated with the westward propagation of the 1993-1995 eddy and a follow-on eddy just south of Amchitka Pass

Figure 39 and 40 display eight velocity (cm s^{-1}) and total kinetic energy (cm^2 s^{-2}) profiles of the entire water column (0-6250 m) during each month represented by an asterisk in Figure 38. The first four plots (Figure 39) display the 1993-1995 eddy as it propagates past Amchitka Pass, while the last four plots (Figure 40) show a relatively stable Alaskan Stream with the second eddy producing a reverse flow in the pass. It is important to note that the period of greatest northward flows through Amchitka Pass are as the trailing edge of the eddy passes by Amchitka Pass (April 1995, ~7.5 Sv). The four plots in Figure 40 display an entirely different flow through Amchitka Pass. Initially, during February 1997, the Alaskan Stream is relatively stable, helping to generate a northward flow through Amchitka pass of ~2.5 Sv. But as the second eddy starts to propagate past Amchitka Pass a southward flow becomes apparent in the model output. In the case of the second eddy the period of greatest southward flow occurs as the eddy approaches Amchitka Pass (November 1996, ~-3.4 Sv). It is also important to note that the period of reverse flow produced by the second eddy lasted from April 1996 until December 1996, with one month (July) during that period displaying a positive volume transport (~0.3 Sv).

Amchitka Pass Part A

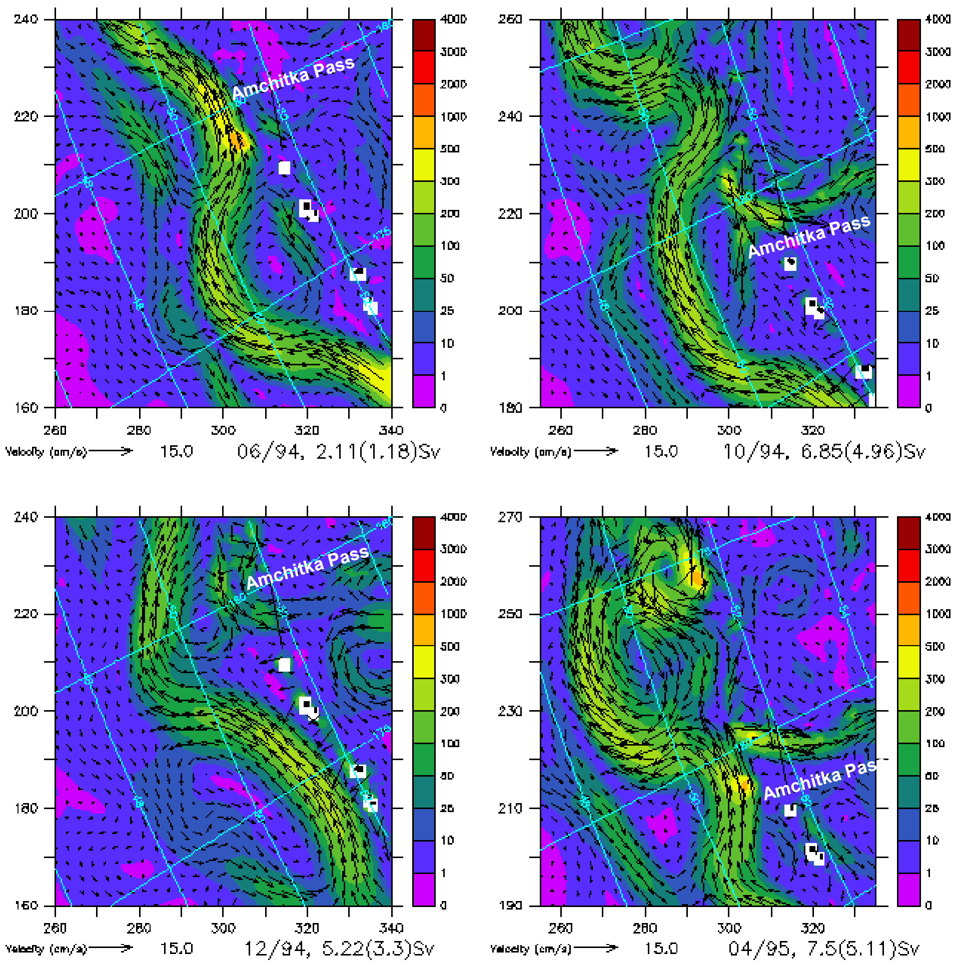


Figure 39. Mean monthly velocity (cm s^{-1}) and kinetic energy of the entire water column near Amchitka Pass during eleven months during mid-1994 to mid-1995. The volume transport in parentheses indicates the volume transport anomaly during the same month. Color shading represents the total kinetic energy (cm^2 s^{-2}).

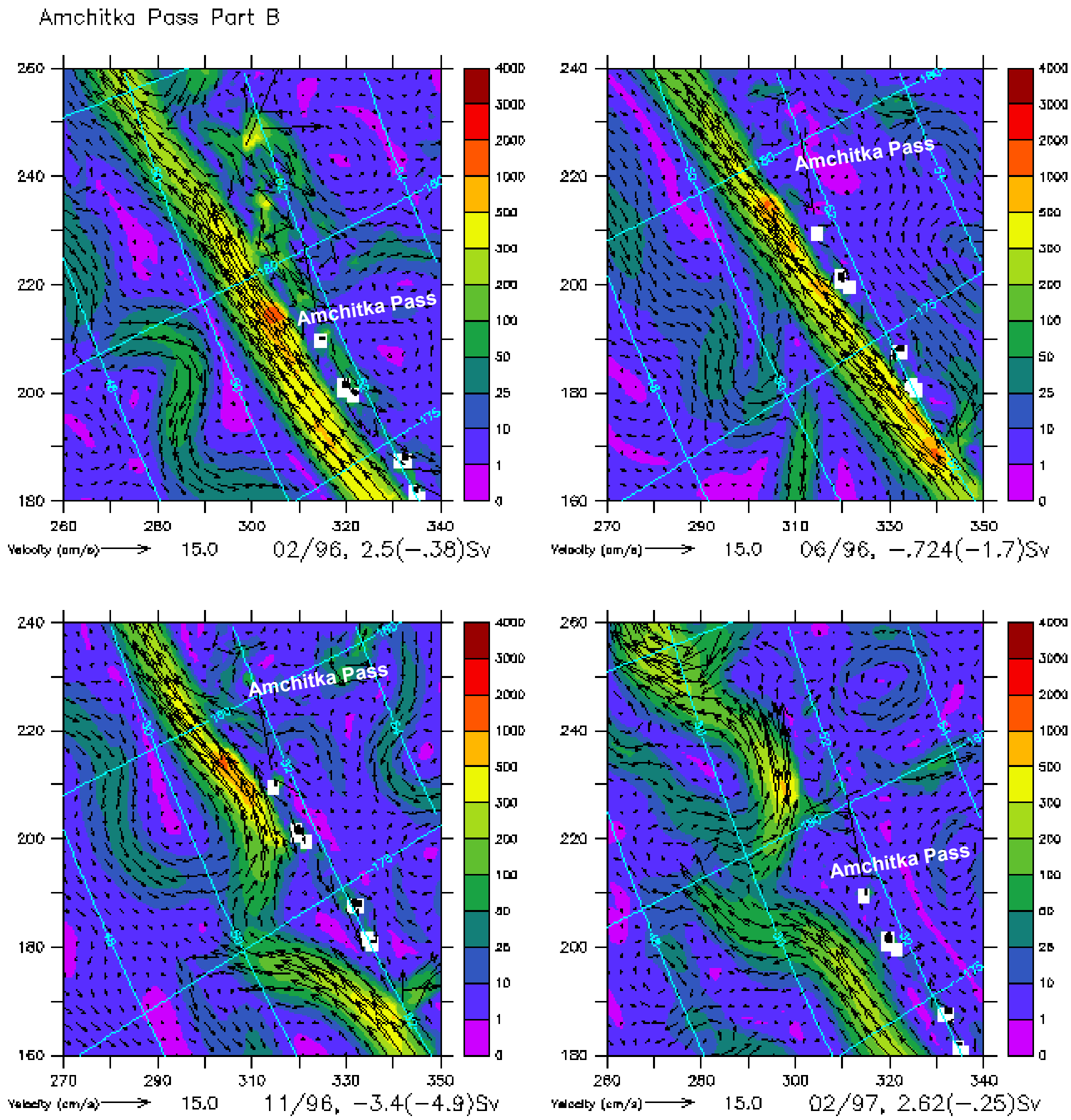


Figure 40. Mean monthly velocity (cm s^{-1}) and kinetic energy of the entire water column near Amchitka Pass during thirteen months in 1996-1997. The volume transport in parentheses indicates the volume transport anomaly during the same month. Color shading represents the total kinetic energy (cm^2 s^{-2}).

The salinity, temperature, and velocity vertical profiles across Amchitka Pass are shown in Figure 41. Extending below ~1600 m, the salinity and temperature profiles depicts fresher and warmer water entering the Bering Sea through the pass on the eastern side. Unlike

the previous two passes, Amchitka Pass allows water reaching a salinity maximum of ~34.8 psu to enter the Bering Sea at depths >1200 m, while the surface salinity is modeled to be ~32.4 psu on the eastern side. The temperature profile demonstrates the ability of warm ($>4^{0}$) North Pacific water to traverse Amchita Pass at depths of ~800 m, while surface temperatures reach 8^{0}. The 25-year velocity profile for Amchitka Pass shows a maximum net northward velocity of ~8 cm s^{-1}, and positive (northward) flow is evident at depths >900 m. There is a weak southward flow (~0-1 cm s^{-1}) near the bottom of the pass.

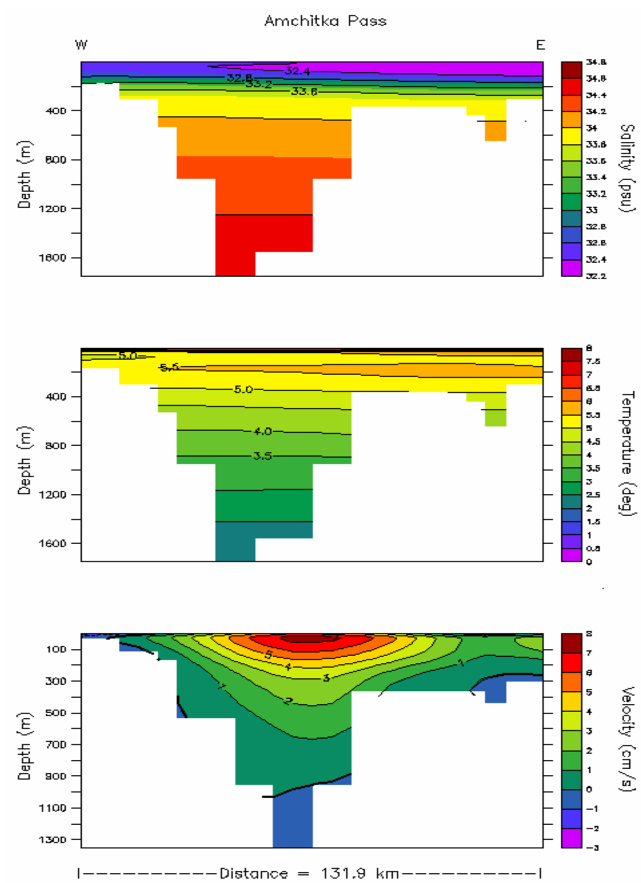


Figure 41. Twenty-five-year mean (1979-2003) profile of salinity (psu), temperature (deg), and velocity (cm s^{-1}) for Amchitka Pass. Positive velocity is directed northward.

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IV. DISCUSSION

Many different estimates have been made of the Alaskan Stream's volume transport throughout the years. Favorite et al. (1974) estimated that the volume transport near the eastern Aleutian Islands was ~12.5 Sv, but the speed of the Alaskan Stream was only referenced to 1000 dB. Later observations by Warren and Owens (1988), in an attempt to investigate the possibility of westward flow below 1000 dB, explored the deep water (4500 m) of the North Pacific Ocean using current meter moorings. Their results indicated that a significant flow existed deeper than 1000 m, and recorded a total volume transport near 175^0 W of 28 Sv. The volume transport measured using the 25-year model discussed in this report was calculated at fourteen different cross sections (Figure 3) along the Alaskan Stream, starting just southwest of Kodiak Island and extending past Amchitka Pass. The 25-year mean volume transport for these fourteen cross sections ranged from a minimum of 33.76 Sv (AS1) to a maximum of 44.33 Sv (AS9 and AS10). The model results suggest a significantly higher magnitude of the volume transport for the Alaskan Stream compared to previous observations, which can be attributed to several different reasons. First, many of the previous volume transport measurements were based on limited in space and time CTD or current mooring data for the Alaskan Stream. In contrast, model estimates of volume transport are derived from velocities computed at each point of a high-resolution (9-km horizontal, 45-level vertical) model grid. Secondly, although more recent Alaskan Stream measurements have involved the collection of data over increasingly longer

periods of time, the lack of long-term, continuous data presents several problems. As seen in Figure 28, southward shifts in the Alaskan Stream can significantly bias transport calculations based on fixed point measurements over the northern portion of the Aleutian Trench, as CTD stations and current meter moorings are then just north of the current. This results in lower estimates of the Alaskan Stream. Also, although the Alaskan Stream generally maintains a steady westward flow, the 25-year model results (see Figure 3) display several long-term deviations from the mean that could affect the overall volume transport. Lastly, while recent full-depth hydrographic studies of the Alaskan Stream (Reed and Stabeno, 1999) have acquired measurements to 6800 m (see Figure 18), they fail to recognize the effect of westward velocities below 10 cm s^{-1}. This has a significant impact on the total volume transport of the Alaskan Stream as AS10 (Figure 19) shows a westward flow between 5 and 10 cm s^{-1} occurring below ~1800 m, and extending to ~2500 m. Also, at AS10 the model calculates westward flow down to ~3500 m. This is in agreement with both Roden (1995), and Chen and Firing (2006), who concluded that past estimates of the Alaskan Stream’s westward flow has been underestimated due to the choice of a shallow 1000 dbar reference level.

Investigation of the northward flow through the Aleutian Island passes, like the Alaskan Stream, has also become more thorough over the last two decades. Recent reports (Reed and Stabeno, 1994; Stabeno et al., 1999) have measured the mean transport through Unimak, Amukta, and Amchitka passes at 0.23 Sv (ranging from >0.50 Sv to 0.1 Sv), 0.6 Sv (ranging from 1.4 Sv northward flow to <0.10 Sv

southward flow), and 0.3 Sv (ranging from 2.8 Sv northward flow to 2.8 Sv southward flow) respectively, concluding that flow is highly variable. They also characterize the typical flow through all three passes as being northward on the eastern side and southward on the western side of the pass. However, the 25-year model output gives significantly different mean volume transports through these three eastern passes. Twenty-five-year mean northward volume transports through Unimak Pass, Amukta Pass and Amchitka Pass were computed to be 0.07 Sv, 1.591 Sv, and 1.886 Sv, respectively. These stark differences can likely be attributed to the lack of long-term observations. Looking at the 25-year time series plots of volume transport for the three eastern passes (Figures 32, 35, and 38) it is evident that large fluctuations occur throughout this period. Consequently, measuring the volume transport through any one of these passes during a shorter period of time might give a significantly larger or smaller result, while a 25-year mean can more accurately determine long-term flow. It is also important to note that while the mean volume transport through each pass has been measured as a positive (northward) flow, there exists the possibility of long periods of southward flow which could greatly affect the water composition of the Bering Sea. In Stabeno and Reed (1992), they observed a considerable deviation from the typical northward flow through Near Strait, stating that the Alaskan Stream ceased flowing northward through this passage starting in summer 1990, and maintained a negative flow until fall 1991. Although the research presented in this report does not include measurements of volume transport through Near Strait, it is evident from Figure 38 that net southward flow during

extended periods of time (approximately one year) is possible. This report has presented evidence that long-duration southward flows through the Aleutian Island passes are often associated with propagating Alaskan Stream eddies (see, for example, Figure 40 and the eddy-driven flow reversal through Amchitka Pass). Eddies propagating along the Aleutian Island arc affect not only the location of the Alaskan Stream, but also the exchange of water between the North Pacific Ocean and the Bering Sea.

Lastly, the question of why the 1993-1995 eddy stalls near Amchitka Pass is revisited. The fact that the eddy moves with seemingly constant speed until it reaches ~180^0 could be due to several reasons. One might be a difference in depth, preventing it from moving further along the Alaskan Stream. Regardless, this question is beyond the realm of this research, but may pose as a significant problem for a following thesis to explore. Ultimately, the fact that the eddy in Figure 40 removes water from the Bering Sea for a period of approximately nine months might have important consequences for not only the local wildlife, but for temperatures and salinities inside the Bering Sea as well.

V. CONCLUSION

The mean volume transport of the Alaskan Stream through the fourteen cross sections (see Figure 2) depicts a strong westward flow along the Aleutian Island arc. The vertical velocity profiles also show that the Alaskan Stream typically extends to at least 3000 m and sometimes extends to near bottom (~6000 m). These findings suggest that observational data may be underestimating not only the strength of the Alaskan Stream, but its influence on the deep waters of the North Pacific as well. The importance of the westward transport Alaskan Stream and eventual contribution to the northward flow through the Aleutian Island passes, likely has a significant effect on the physical and biological structure of the Bering Sea (Okkonen, 1992). As an example, a decrease in northward flow would alter both the temperature and salinity of the Bering Sea subsurface water (Stabeno and Reed, 1992), eventually affecting the productive ecosystem which exists in the region. Conversely, an increase in flow through the Aleutian Island passes could be a contributor to the warming in the Arctic Ocean, as more warm, fresh water entering the Bering Sea ultimately affects the water properties transported northward through the Bering Strait. The formation of eddies along the Alaskan Stream seem to be the major cause of deviations in westward flow, creating southward shifts in the current which can significantly alter northward transport through the Aleutian Island passes over extended periods of time. Lastly, in order to improve the model output, especially near the Aleutian

Island passes, tidal forcing must be included in future simulations (Maslowski et al. 2005).

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